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HYDRAULIC SYSTEM VULNERABILITY STUDY

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May 1968

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FOREWORD

This report was prepared by the Vought Aeronautics Division of the LTV Aerospace Corporation, Dallas, Texas, under Air Force Contract F33615-67-C-1747, BPSN 7(68 0100 61430014). The program was administered under the direction of the Aerospace Power Division, Air Force Aero Propulsion Laboratory; Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. R. J. Smith (APIE-3) acting as Project Engineer.

The report covers work conducted between June 1967 and February 1968. It was released by the author 29 February 1968.

The program was conducted with Mr. C. G. Brock as principal investigator, under the direction of Mr. H. E. Reynolds, Project Engineer – Applied Research and Development. The author wishes to acknowledge the assistance of Messrs. M. Ernest, H. Franks, W. D. Privett, J. E. Rasmusen, S. L. Reichert, R. C. Slay, C. B. Welborn, and A. G. Wetzel.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

Aircraft hydraulic systems are presently designed with emphasis placed on satisfying performance requirements with minimum penalties in weight, reliability, maintenance, and costs. Results from limited war analyses have indicated the vulnerability of current hydraulic systems. Vulnerable areas of these systems were then protected with armorplate, resulting in mission penalties. A hypothetical airplane was defined, based on the F-8 configuration, with twin engines and a weight of 45,000 pounds. Conceptual system designs for this airplane were defined with increased redundancy incorporating backup or isolation features without the use of armorplate. These systems were assessed for vulnerability/survivability, reliability, maintainability, weight, performance, and system cost. These assessments provided system rating values and inputs for operational costs. Methods used to determine system value ratings placed emphasis on significant rating values. Two different costing methods were used. One method used cost equations, which accounted for initial investment and operating costs, to determine ten-year costs. The second method applied cost deltas, derived from a baseline system, to changes in survivability, reliability, maintainability, weight, performance, and system cost with respect to the baseline system. Results of the assessments and costing were compared to the baseline system. The increase in redundancy (increase over the baseline system) resulted in most of the systems having probabilities of survival greater than the baseline system with armorplate. Further increase in probability of survival was achieved with the use of isolation and backup subsystems. Rankings by the value rating and two costing methods were compared, and five selections were made. A five-year development plan was prepared. This plan extends the activity of the program reported herein into a three-phase program involving component development, system evaluation, and flight test evaluation.

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SECTION I

INTRODUCTION

The traditional approach to the design of hydraulic systems for military aircraft has been to establish the operational or functional requirements; select the best, most reliable, lightweight hardware that will do the job; then design the installation to fit in whatever space is available after most of the high priority systems have been installed. These traditional hydraulic systems usually contain dual subsystems for flight controls and means of isolating utility functions. This approach results in an acceptable hydraulic system from the standpoint of operation, and may be one of the lightest, most easily maintained, economical systems possible. On the other hand, this approach may result in some very serious deficiencies when the aircraft is exposed to battlefield conditions.

Aircraft losses due to small arms gunfire damage in Southeast Asia are sufficiently high to warrant a serious look at how aircraft survivability can be improved. Although aircraft-loss statistics are not always complete, it is apparent that many losses are due to hits in the hydraulic systems that cause catastrophic failure of the aircraft control system and subsequent loss of the aircraft. One approach to improving survivability is to shield selected components or highly vulnerable areas of the aircraft with armorplate. This approach, although effective, has a number of disadvantages. Some of these are added weight and complexity of maintenance of the equipment, decreased payload, high installation costs, and incomplete protection. Another approach which is currently in use is that of using power packages to isolate certain critical portions of the system. Other approaches that are in some stage of development include the use of flywheel power, pulsating flow, and automatic failure detection and isolation. These latter approaches consider improving survivability from a system standpoint; however, there is also much activity in component design to reduce vulnerability by new packaging techniques and the use of protective materials. One of the obvious disadvantages of these system approaches is the added weight of the extra pumps, valves, tubing, etc.; however, if the aircraft survivability has been increased, it may be well worth the small loss in payload-carrying capability.

The Air Force Aero Propulsion Laboratory contracted with Vought Aeronautics Division of LTV Aerospace Corporation to conduct a program of study to determine what design approaches might be used to design in hydraulic system survivability without significant penalty in performance, weight, cost, maintainability, and reliability. In addition, VAD was to make a qualitative and quantitative evaluation of these factors for hydraulic system concepts in a hypothetical aircraft.

The program was divided into two phases of study. The first phase was to establish the hydraulic system design criteria for the hypothetical aircraft and to define all of the hydraulic system concepts that would be considered in the preliminary screening. The screening was to be made on the basis of weighted importance of survivability, reliability, weight, etc., and a selection was to be made on two or three preferred concepts for more detailed evaluations during Phase II. The ultimate objective was to arrive at the "best" of the final three concepts considered in Phase II and make recommendations on development of that concept for improved survivability hydraulic systems.

The objective of the program was achieved with Phase I screening resulting in 11 concepts selected for detailed definition and evaluation in Phase II. The elimination of any of these candidate concepts, without a more detailed evaluation in Phase II, would have probably eliminated some of the more promising, high-survivable concepts. These concepts were less familiar to the evaluation team and, consequently, may have been overly penalized in initial screening; therefore, in order to be more objective, all concepts were retained for Phase II.

The complete description of the evaluation techniques is presented in Section VII of the report. Detail data used in the evaluations is presented in the appendices. The concept comparisons denoted as Ten-year System Costs and Value Rating are presented in Sections VIII and IX, respectively, of this report. A delta cost method was added to the study to show concept cost variations to the baseline using cost per incremental change in survivability, reliability, etc.

SECTION II

SUMMARY

In order to establish a common means of comparing the hydraulic system concepts, a "fighter attack" type airplane was defined. The model or hypothetical airplane was based on a redesigned F-8 airplane with two engines and weighing 45,000 pounds. The aircraft/mission performance requirements were defined. A force size of 1,000 available aircraft was required to deliver a total payload of 18.9 x 10^6 tons over a period of ten years. This was to be accomplished by five missions per aircraft per week. The duration of each mission was 1.5 hours. The airplane was defined to contain all systems, including the hydraulic system. Thus, the only variable in the total airplane definition was the hydraulic system. Functional elements and their operational requirements were defined for operation by the hydraulic system. These were limited to typical elements necessary to support a normal flight mission.

The system was defined to include all components required to generate, transmit, control, and utilize power. Interfaces were defined as power or control inputs from the electrical system, flight control system, pilot, and engine. The performance modes of each system were defined as normal, intermediate, and emergency. The latter two modes occurred after the system sustained battle damage. After one hit, the system is in the intermediate mode; after two hits, it is in the emergency mode. The threat considered was .50 cal HP. In each mode certain functions were required to be operable with full or reduced capability after each loss. The functions required in the emergency mode were the ailerons, UHT's, wheel brakes, and landing gear. These functions were identified as critical functions; the subsystems which operate these functions were identified as critical subsystems.

Increasing survivability through system design was emphasized in the selection of concepts. Many concepts were investigated; these incorporated increased redundancy, isolation, and backup subsystems as potential means of obtaining high survivability. Screening of these preliminary concepts resulted in the identification of 11 concepts for further definition. These concepts were defined as "pure" concepts, representing various means of utilizing hydraulic, electrical, and pneumatic power.

The preliminary concepts were expanded into system definitions to include all major components necessary to support the required functions. Each system definition was based on feasible operating principles, with problem areas recognized and general solutions provided to the depth necessary to facilitate evaluation. Arrangement of subsystems was dependent on the functions required for each performance mode. The functions were grouped according to the number of failures or hits required to lose each function; i.e., three hits were necessary

to lose aileron capability. Block diagrams were prepared to relate power sources and components to the functions and to identify critical and noncritical subsystems. Component definition was based on current hardware and sized by the relationship of requirements for the hypothetical airplane and the F-8 airplane. Components were located in the hypothetical airplane to facilitate vulnerability analysis and maintainability assessment.

A baseline system was defined for comparison with all systems. This system represented current design with its dual hydraulics for flight control functions and a separate utility subsystem; this resulted in double redundancy to the critical functions. Armorplate was added to obtain the highest probability of survival for this system. The other systems contained triple redundancy for the critical functions, with separation or isolation of all noncritical functions. Eleven "pure" concepts were expanded into system definitions; these were classified as redundant, isolated, or backup systems. As a result of initial evaluations,three additional hybrid or modified systems were defined. All systems defined and evaluated are listed below:

Concept No.	Type	Name
1	Redundant	Baseline
2	Redundant	Three Hydraulic Sources
3	Redundant	High Pressure
4	Backup	Electromechanical Backup
5	Isolated	Flywheel Power
6	Backup	Electrohydraulic Backup
7	Isolated	Five Hydraulic Sources
8	Isolated	Pulsating Flow
8A	Isolated	Modified - Pulsating Flow
8B	Isolated	Modified - Pulsating Flow
9	Isolated	Electrohydraulic Power Pack
9A	Isolated	Modified - Electrohydraulic Power Pack
10	Isolated	Motorpump Isolation
11	Isolated	Automatic Failure Isolation

Each system was defined with emphasis placed on obtaining systems more survivable than the baseline. As each system was analyzed for its probability of survival, it was assessed for reliability, maintainability, weight, performance, and cost. Each assessment area provided rating values and inputs for operational costs. The rating values for each system were combined into a composite rating, which emphasized the significant values. Ten-year system costs were derived by two methods using the cost inputs from the assessments. One method used cost equations to estimate costs for each system. The second method used cost deltas from the baseline total ten-year system cost.

Redesigning the baseline system by adding redundancy with isolation or backup features resulted in greater survivability than could be obtained by adding armorplate to protect vulnerable or critical areas. Three independent system rankings were determined from system value ratings and ten-year system costs. An analysis of these rankings, with emphasis placed on the cost equation ranking, resulted in the selection of the five best systems in terms of cost/effectiveness. These systems are listed below in the order of ranking.

Concept No. 6	Electrohydraulic Backup
Concept No. 4	Electromechanical Backup
Concept No. 7	Five Hydraulic Sources
Concept No. 5	Flywheel Power
Concept No. 10	Motorpump Isolation

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SECTION III

AIRPLANE DEFINITION

1. INTRODUCTION

The airplane was defined as a complete airplane containing all systems except the system required to power the flight controls and utilities. Definition of this system was determined after the functions, or functional elements, were identified. Since the activity of this program involved the definition, evaluation, and comparison of system concepts, the types of functions were not critical. In view of this, an airplane with only essential or conventional functions was derived. The model or hypothetical airplane was derived from a currently operational VAD aircraft and was defined only to the extent necessary to support system definition.

2. DESCRIPTION

The hypothetical airplane, shown in Figure 1, is a swept wing vehicle with twin turbojet engines. The gross takeoff weight is 45,000 pounds. A dimensional scale factor of 1.32, based on a ratio of weights, was applied to the selected VAD airplane.

a. General Arrangement

The general arrangement of major elements is shown on Figure 1. Fuel cells and engines are shown since they will provide shielding of the systems against ground fire. Major compartments are shown to facilitate location of system components. The tripod landing gear retracts aft into wheel compartments.

b. Functional Elements

The functional elements are limited to those necessary to support normal airplane operations. These elements are:

(1) Flight Controls

- (a) Aileron
- (b) Unit horizontal tail (UHT)
- (c) Rudder
- (d) Spoiler
- (e) Speed Brake

(2) Utilities

(a) Landing Gear

(b) Wheel brakes

(c) Flaps

(d) Arresting gear

(e) Air refueling probe

3. PERFORMANCE

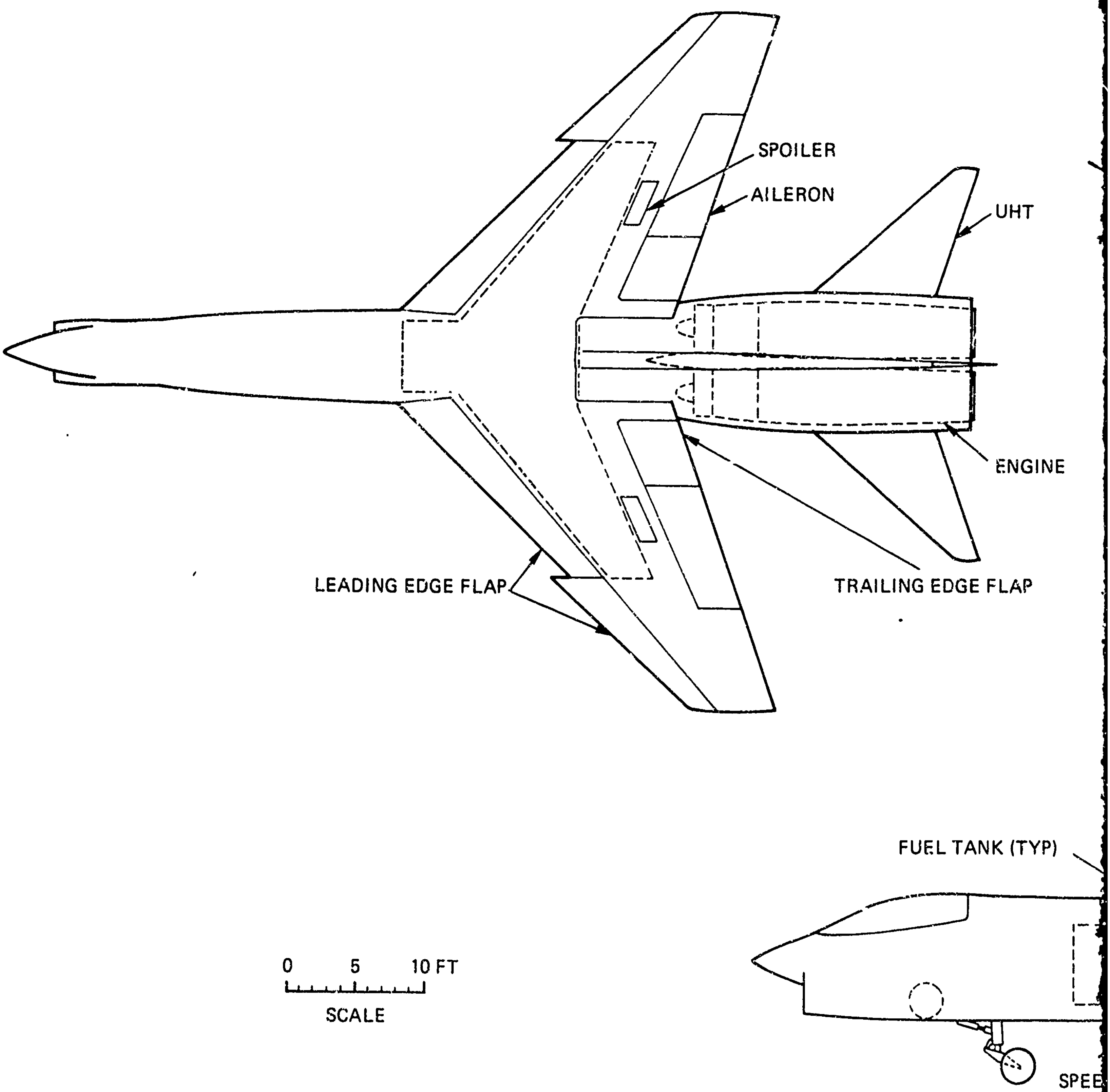
In order to establish a means of comparing one concept against another, it was necessary that some general performance characteristics be established. There were two basic types of performance requirements. One was that associated with the assumed operational use of the aircraft (mission oriented), and the other was that associated with the hydraulic system functional performance.

a. Airplane

Since one of the criteria for making the final selection of concepts is overall cost/effectiveness, it was determined that a mission life and force size would be required to produce this type of information. Detail cost/effectiveness studies themselves are very complex, and much beyond the scope of this program; however, a simplified approach to the system costing was assumed during this study. A detail description of the total system cost model is presented in Section VIII of this report.

Aircraft/mission performance requirements assumed for this study were as follows:

Force size:	1,000 aircraft operational at all times
Total life:	10-year operational
Missions:	5 per aircraft per week
Mission Duration:	1.5 hours per mission
Payload/Weight:	The total weight of the deliverable payload plus the hydraulic system was 14,744 pounds. It was assumed that every additional pound of hydraulic system would deduct a pound from the deliverable payload.
Total payload:	Total delivered over 10 years 18.9×10^6 tons



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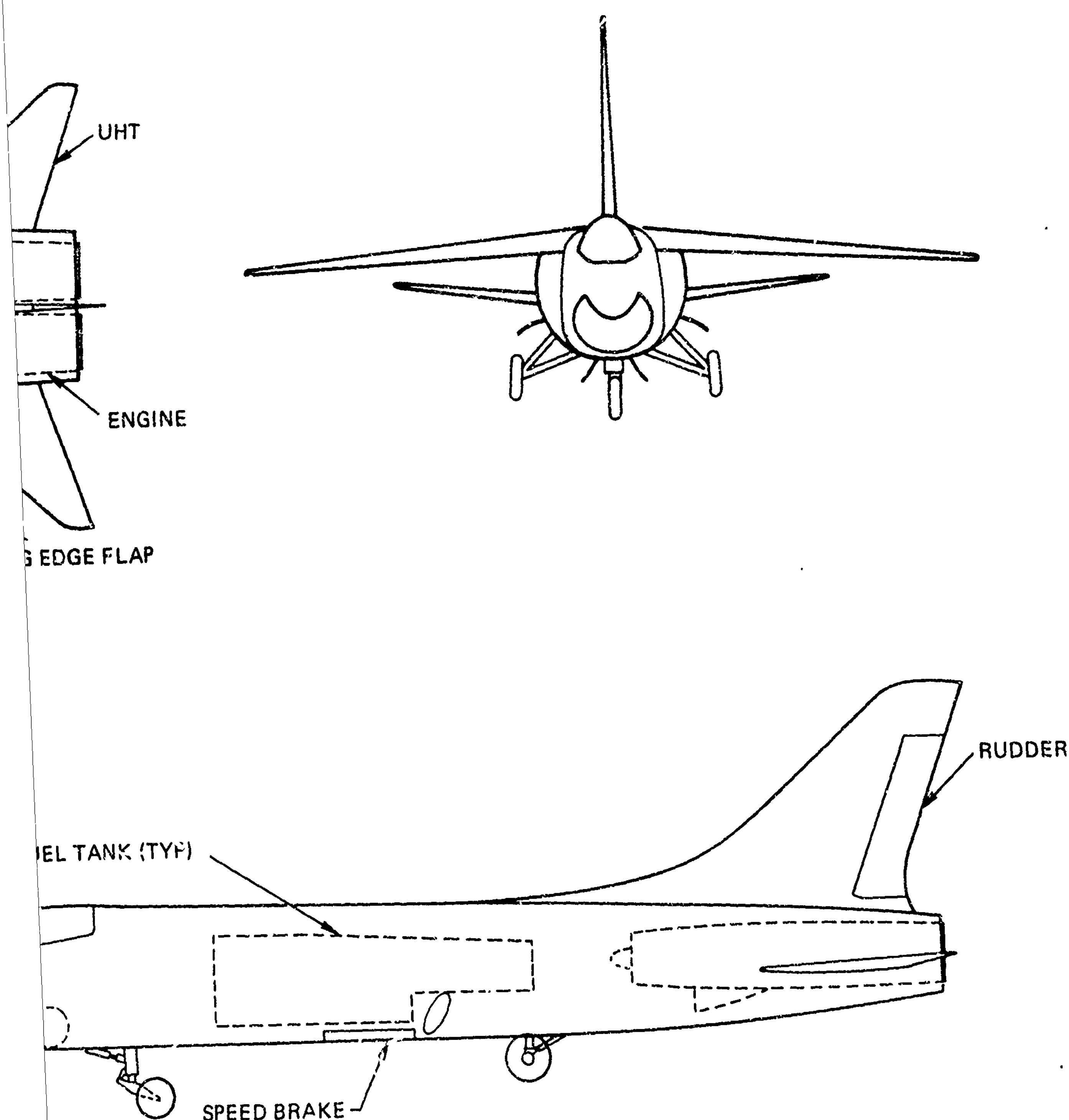

Figure 1. Hypothetical Airplane

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b. Functional Elements

Table I shows the load, rate and deflection or travel required for each functioning element to support performance of the airplane. Moments are about the hinge line or pivot point and are peak values occurring during motion. Rates and deflections are under load. Utility elements generally function in some required time; however, to facilitate component sizing in each system, this functioning or operating time is expressed as a rate. The requirements for wheel brakes are not shown; a hydraulic power of 1.0 horsepower was assumed for each wheel brake.

TABLE I OPERATIONAL REQUIREMENTS OF FUNCTIONAL ELEMENTS

FUNCTION	HINGE MOMENT (FT-LB)	RATE (DEG/SEC)	TOTAL DEFLECTION (DEG)
Aileron	26,000/Side	70	50
UHT	60,000/Side	25	40
Spoiler	6,000/Side	200	50 (UP)
Rudder	7,000	120	34
Speed Brake	93,000	25	60 (DN)
Air Refueling	1,000	6	30
Landing Gear			
Main Gear	5,000/Side	18	90
Main Gear Door	2,600/Side	30	60
Nose Gear	5,500	30	90
Nose Gear Door	400	45	90
Flaps			
L.E. Inboard	14,000/Side	8	40 (DN)
L.E. Outboard	8,000/Side	7	35 (DN)
Trailing Edge	3,000/Side	8	40 (DN)
Nose Gear Steering	4,000	60	120
Arresting Gear	2,200	25	75

SECTION IV

DESIGN CONSIDERATIONS

1. INTRODUCTION

After the airplane and its functional elements were defined, certain considerations or ground rules were established before defining the systems which operate the functional elements. Among these considerations were design allowances for ground fire damage, identification of operating modes and necessary functions, assumptions to facilitate system definition and evaluation, and interface definitions which describe the extent or scope of system definition.

2. INTERFACES

System, as used in this report, contains all the components required to generate, transmit, and utilize power at all functional elements listed in Section III. Each system is divided into subsystems. A subsystem is an independent portion of the system which contains one or two engine-driven power sources (electrical, hydraulic, or bleed air) and all components to the functional elements connected by tubing and wiring. All subsystems are separated such that a failure of any component in one subsystem will not affect the other subsystems. A subsystem may be further divided into major and minor circuits. A major circuit contains the power source(s) and all components connected by tubing and wiring; a failure in this circuit will cause loss of the subsystem. A minor circuit is dependent on the major circuit for power and is isolated such that a failure will not affect the major circuit, thus will not cause loss of the subsystem.

The scope of system definition is limited by the definition of interfaces. Each interface imposes a constraint on the capabilities of the system. These interfaces, as defined below, are typical of current aircraft.

a. Electrical

Electrical power is available to drive motors in motorpump packages and electromechanical actuators, to energize solenoid valves, and to provide control inputs to electrohydraulic servo valves.

b. Mechanical

Mechanical interfaces are defined as engine pads for driving pumps and generators, control linkage at control valves on flight control valves on flight control actuators, and linkage at manual selector valves.

c. Pneumatic

Engine bleed air is available for driving low power motors. Stored air is available for charging accumulators.

d. Functional elements

All actuators connect to the functional elements and airframe. The interface is the attaching point for the actuator.

3. THREAT

The hypothetical airplane and the system defined herein are exposed to small arms ground fire. The threat for the vulnerability analysis was selected as .50 cal AP because it represents the upper limit of the small arms environment. A more severe threat was not considered in view of the fact that a larger projectile (particularly a high explosive type) could and possible would severely damage a number of aircraft systems on any one hit.

Each system, except the baseline, must be designed such that it remains operational after a minimum of two hits. A single hit in a subsystem kills only that subsystem; thus three hits should be assumed in three subsystems. The baseline system is recognized as current design with failure philosophy such that only two hits would kill it. A more detailed discussion of the threat is included in Section VII.

4. PERFORMANCE MODES

The performance mode of each system, except the baseline, is a function of the number of hits or losses sustained by the system. Each hit represents the loss of any one subsystem. The performance modes are normal, intermediate, and emergency. With each hit, or subsystem loss, certain functions are permitted to be lost. Table II lists the functions required for each performance mode.

a. Normal Mode

The system is in the normal mode when all subsystems and functional elements are operating to design performance requirements as specified in Table I.

b. Intermediate Mode

When any one subsystem is lost, the system is in the intermediate mode. Maximum allowable losses are the nose gear steering and arresting

gear functions. Reduced performance capability is allowed for the flight control functions, provided further loss (emergency mode) can be sustained. The remaining functions in Table II must have full capability.

c. Emergency Mode

A system is in the emergency mode when any two subsystems are lost. The functions that must be available in this mode are ailerons, UHT's, wheel brakes, and landing gear. Each flight control function must operate at a minimum of one-third the rate and load shown on Table I. Each utility function must have full capability. The emergency mode functions were selected to provide control of the airplane and landing capability at the end of its mission. Although not considered in this study, an alternate emergency mode could have reduced the functions to those necessary to allow pilot ejection in a friendly area. Minimum control surface capabilities were based on the following considerations for emergency mode: (1) at maximum sea level flight ($M = .9$), the airplane must be capable of a 3g pullup; and (2) lateral control capability must provide the airplane with a peak steady rolling velocity of 15 degrees per second.

The functions required in the emergency mode are identified as critical functions. The subsystems which operate these functions are identified as critical subsystems. All other functions and associated subsystems are noncritical.

TABLE II PERFORMANCE MODE FUNCTION REQUIREMENTS

FUNCTION	PERFORMANCE MODE		
	NORMAL	INTERMEDIATE	EMERGENCY
Aileron	F	R	R
UHT	F	R	R
Wheel Brakes	F	F	F
Landing Gear	F	F	F
Spoiler	F	R	
Rudder	F	R	
Speed Brake	F	R	
Air Refuel	F	F	
Flaps	F	F	
Nose Gear Steering	F		
Arresting Gear	F		

F - FULL CAPABILITY

R - REDUCED CAPABILITY

SECTION V

CONCEPT SCREENING

1. INTRODUCTION

Increasing survivability through system design was emphasized in the selection of system concepts. It was recognized that a potential increase in survivability may be realized through increasing redundancy of critical functions, isolating critical and noncritical functions, or by the use of backup or standby systems. Many system concepts incorporating these features were examined as potential candidates for definition and evaluation. This examination or screening considered the potential advantages and feasibility of a concept, duplication or similarity among the concepts, representation of a variety of approaches, and the program schedule. The preliminary concepts were defined as "pure" concepts utilizing consistent design principles and solutions for all related functions (i.e. flight controls).

2. CONCEPTS SCREENED

Eighteen preliminary concepts were screened. These include the following:

(1) Improved baseline

(2) Three hydraulic systems with triple tandem actuators at the critical functions

(3) Three hydraulic systems with one dual tandem and one single actuator at each critical function

(4) Three hydraulic systems with three single actuators at each critical function

(5) Three hydraulic systems utilizing high pressure (greater then 3,000 psi)

(6) Four hydraulic sources with motorpump used for power transfer

(7) Five hydraulic sources with separate power sources and subsystems for critical and noncritical functions

(8) Electromechanical backup actuators for the critical functions

(9) Electrohydraulic backup using electric motors to power isolated hydraulics for critical functions

(10) Pneumatic backup actuators for the critical functions

(11) Hydraulic backup utilizing third hydraulic subsystem as standby

(12) Ram air turbine backup using engine bleed air to extend turbine package

(13) Flywheel power utilizing engine bleed air to drive flywheels used to power isolated hydraulics for noncritical functions

(14) Motorpump isolation to separate critical and noncritical functions in the same subsystem

(15) Electrohydraulic power packages using maximum electrical power and transmission to isolated hydraulics driving all functions

(16) Pulsating flow hydraulics to achieve maximum system isolation by increasing number of subsystems

(17) Failure isolation utilizing mechanical fuses

(18) Failure isolation utilizing automatic detection and isolation techniques

3. CONCEPT SELECTION

The screening effort reduced the number of concepts to eleven for further definition.

(1) Baseline

Although not subjected to screening, this concept was established as the reference concept for comparison to each concept in the evaluation. Dual hydraulic subsystems are used for flight control functions, and a third hydraulic subsystem is used for utility function.

(2) Three Hydraulic Sources

The three hydraulic subsystems power the flight controls and share other functions. This concept provides increased redundancy.

(3) High Pressure

Components of the three-hydraulic system are reduced in size by an increase in system pressure to 9,000 psi for the purpose of reducing vulnerable areas.

(4) Electromechanical Backup

A backup or standby subsystem was added to the baseline concept for use when both hydraulic subsystems are lost. Electromechanical actuators power the critical functions.

(5) Flywheel Power

Maximum separation or isolation of critical and noncritical functions is obtained with this concept by the use of engine bleed air to drive flywheel packages for noncritical functions.

(6) Electrohydraulic Backup

This concept is similar to the electromechanical backup concept but uses electrical motor-driven hydraulics for the critical functions.

(7) Five Hydraulic Sources

Like the flywheel power concept, maximum separation of critical and noncritical functions is obtained. Additional engine-driven pumps power the noncritical functions.

(8) Pulsating Flow

Three alternators convert conventional flow hydraulics from three power sources into alternating or pulsating flow transmitted by three common lines. Conversion back to conventional flow is accomplished at the actuators for each function. Numerous transformers are used for maximum isolation within the system.

(9) Electrohydraulic Power Pack

Electrical power is transmitted to power packages located near the functioning elements. The power packages convert electrical power to hydraulic power for all functions.

(10) Motorpump Isolation

Hydraulically driven motorpumps are added to the three-hydraulic system to isolate the noncritical functions. These units act as mechanical links between subsystems.

(11) Automatic Failure Isolation

This concept is similar to the motorpump isolation concept except isolation occurs after degradation is detected. Sensors in the noncritical circuits detect an undesirable condition and transmit this information to a control logic unit. A signal is then transmitted to a shutoff valve isolating the noncritical function.

SECTION VI

SYSTEM DEFINITION

1. SCOPE

The concepts selected in Section V were expanded to include major components necessary to support the required functions. Each system includes the power sources and the means of utilizing the power. Each system is based on feasible operating principles with problem areas recognized and general solutions provided to facilitate evaluation. Hardware development is assumed matured for the purpose of definition. Ground checkout procedures were not included in the definition; however, servicing requirements are identified. Each system is separated into subsystems, as defined in Section IV, to minimize the vulnerable or critical areas. System operation and component descriptions were defined to the level necessary for evaluation of the system.

2. APPROACH

Each concept was developed to satisfy the requirements of Section IV. Sufficient design was performed to present the concept as a physically defined system. Breakdown of the system into subsystems was based on a separation of critical and noncritical functions. Separation of these functions was achieved with complete subsystem separation or by the use of isolating devices not normally used for control or shutoff.

a. System Arrangement

Two levels of block diagrams were prepared. The first level relates power sources to the functions grouped according to type (utility and flight controls) and number of failures required for function loss. Table III presents this grouping. Those functions requiring three failures for function loss are critical functions. Each failure is the total loss of a subsystem servicing the function. The second level defines all components within the scope intended; these block diagrams are included in Appendix I.

b. Component Sizing and Selection

Available components satisfying the general requirements were used as much as possible. New components were defined with features of similarity identified. Actuators were sized to the required loads and for the motion geometry derived from the operational aircraft. Pumps and generators were sized for the operating condition (combination of functions in Table III) demanding the greatest load. This was assumed to be a flight condition requiring operation of the aileron, UHT, spoiler, rudder, and

TABLE III

FUNCTIONAL GROUPS

No. Failures to Lose Function →	3	2	3	2	1
Group →	1	2	3	4	5
Function ↓	Flt Cont	Flt Cont	Util	Util	Util
Aileron	X				
UHT	X				
Spoiler		X			
Rudder		X			
Speed Brakes		X			
Refuel		X			
Wheel Brakes			X		
Landing Gear			X		
Flaps				X	
Arresting Gear					X
N. G. Steering					X

speed brake. Although the demands on each surface varied, it was further assumed that, collectively, the demand on the power sources would be 60% of the sum of the maximum demands of each surface.

c. Component Location

Components were placed in the aircraft at locations considered normal for each component type with the wheel wells accumulating the majority of components other than pumps and actuators. All actuators were placed as near the functional element as possible. Components were located in a three-axis coordinate system to facilitate vulnerability analyses.

d. Transmission Lines

Sizes and lengths of the transmission lines were determined considering flow distributions and location of components. Transmission lines connected components directly along each axis of the coordinate system with no allowance for obstructions. Sizing of hydraulic tubing assumed a maximum fluid velocity of 30 feet per second.

e. Component Configuration

The shape of each component was assumed to be a parallelepiped in order to facilitate area and volume calculations. Available components were dimensioned in this shape and used as the basis for determining dimensions for system components.

f. Failure Analysis

By definition, a failure of any component causes complete loss of the subsystem containing the component. Each system was designed to allow the failures in Table III before loss of the function(s). After complete definition of the system, the effects of losing components were analyzed to determine conformance with these requirements.

3. SYSTEM DESCRIPTION

a. Introduction

The description of each system includes system operation, special features, and problem areas in addition to significant procedures used in developing the system. All systems contain redundant subsystems to the critical functions. Two classifications of systems are presented: pure and modified. The pure system utilizes a particular design principle (i.e., pulsating flow) in the definition of each subsystem, while the modified system combines design principles (i.e., pulsating flow and conventional direct flow). The modified systems were defined after the pure systems were evaluated and certain advantageous features or principles recognized. Further classification of each system is based on its relationship to the

baseline system and the relationship of critical and noncritical functions. Types are defined as follows. All systems are listed in Table IV.

(1) Redundant - The baseline system contains two hydraulic inputs (two independent actuators) to the critical functions. Those systems which contain an additional input are typed as redundant.

(2) Isolated - Each hydraulic subsystem in the baseline system share both critical and noncritical functions. When these functions are serviced by separate power sources or separated within a subsystem, the system is an isolated type.

(3) Backup - This type covers the system that utilizes a standby or backup subsystem to service critical functions when the system is in the emergency mode.

b. General Description

All systems convert engine power into a form utilized at each function. Efficiencies of power generation or conversion components are considered; however, transmission losses are neglected. Separate single actuators are utilized in all systems except the baseline. The baseline system utilizes tandem actuators as the state-of-the-art for dual hydraulic systems. Flight control subsystems are simplified by applying hydraulic power directly to actuator control valves integral with the actuators; feel isolators and autopilot actuators are omitted.

Each concept provides the same operating characteristics in the normal mode of operation. Each concept satisfies the minimum allowable operation in the emergency mode; however, the operating characteristics may vary due to inherent system capabilities.

The landing gear is free fall in the aft direction. In normal operation the gear is powered for extension; however, upon loss of this subsystem, the free-fall capability is considered the emergency mode operation.

Isolation of functions within the subsystems is accomplished with motorpump combinations utilizing electrical or hydraulic motors or automatic shutoff valves. Valves normally used to select functions are not used for isolation.

The backup system is designed to provide lower rate and load capability since it is operable only after loss of both hydraulic subsystems normally in operation.

Problem areas were recognized and general solutions provided to allow evaluation of each system. Parallel actuators connecting a common element (i.e., aileron, UHT, etc.) introduce synchronization requirements to prevent racking moments and additional installation considerations.

TABLE IV

SYSTEM LIST

Concept No.	Type	Title
1	Redundant	Baseline
2	Redundant	Three Hydraulic Sources
3	Redundant	High Pressure
4	Backup	Electromechanical Backup
5	Isolated	Flywheel Power
6	Backup	Electrohydraulic Backup
7	Isolated	Five Hydraulic Sources
8	Isolated	Pulsating Flow
8A	Isolated	Pulsating Flow - Modified
8B	Isolated	Pulsating Flow - Modified
9	Isolated	Electrohydraulic Power Pack
9A	Isolated	Electrohydraulic Power Pack-Modified
10	Isolated	Motor pump Isolation
11	Isolated	Automatic Failure Isolation

split surfaces would minimize the system problems and would provide greater independency of the subsystems; however, this approach would not influence system evaluation which considers the system limited at the point of power utilization. Backup actuators are in parallel with single actuators for critical functions (i.e., aileron, UHT). When not powered, the backup actuators must move freely without restricting the operating actuators. Reversible ballscrews and fluid bypassing devices can accomplish this. Definition of failure detection techniques requires the identification of failure types and the followup action required. Each system is designed so that the transition from normal mode to emergency mode requires no pilot action; however, he must be informed of the reduced functional capabilities (i.e., loss of one subsystem loses arresting gear capability). The extent of any detection system may be equally applicable to all systems. Therefore, detection techniques were not defined for the conceptual level but would require investigation as the system was further developed. For the conceptual definition, environmental conditions (i.e., temperature, vibration, etc.) were neglected. It is recognized that system startup with a fluid temperature of -65°F must be considered in the detail design. In this study such a consideration would not influence the relative differences in the systems.

c. Pure Systems

(1) Baseline (Concept No. 1)

This system, shown in Figure 2, represents current design practices applied to the hypothetical aircraft. Dual hydraulics (subsystems 1 and 2) are provided to all flight control functions. Utility functions are serviced by a separate hydraulic source (subsystem 3). Functions powered by each subsystem are shown in Table V. All flight control functions, except speed brake and refuel, are powered by tandem actuators. Functions powered by subsystems 3 and 4 use common actuators and shuttle valves. HPS 1 and HPS 3 each contain one engine-driven pump; HPS 2 has two separate engine-driven pumps. Pneumatic charged accumulators provide emergency backup power (subsystem 4) for the critical utilities. Subsystems 3 and 4 are not entirely independent, since each emergency accumulator is dependent on subsystem 3 for its fluid supply. Partial independence is obtained with the use of the shutoff valve shown.

Subsystems 1 through 4 are critical subsystems, since they provide power to the critical functions of groups 1 and 3. When the system is in the emergency mode, group 1 functions are powered by subsystems 1 or 2, and group 3 functions are powered by subsystems 3 or 4. In applying current design practices, it was recognized that the baseline system would not satisfy the failure requirements of Table III (i.e., loss of two subsystems could cause loss of aircraft). Armorplate was added to protect components only, and this baseline system was identified as Concept No. 1A. The addition of armorplate reduced the total vulnerable area by 40% and increased the system weight by 122%. The armor provides protection from lethal hits for any projectile approach angle below the aircraft horizontal reference plane and is provided equally for all

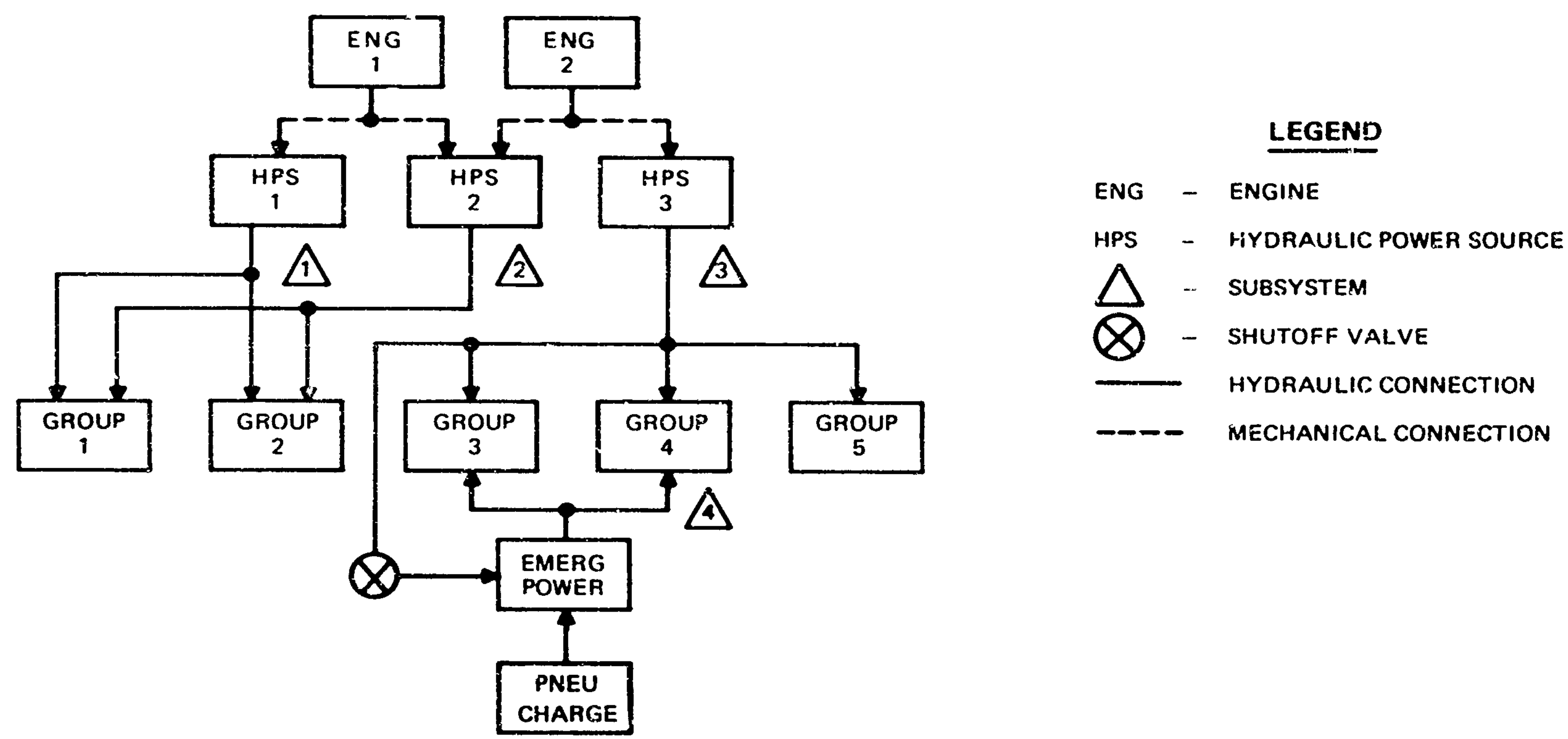

Figure 2. Concept No. 1 Baseline Block Diagram

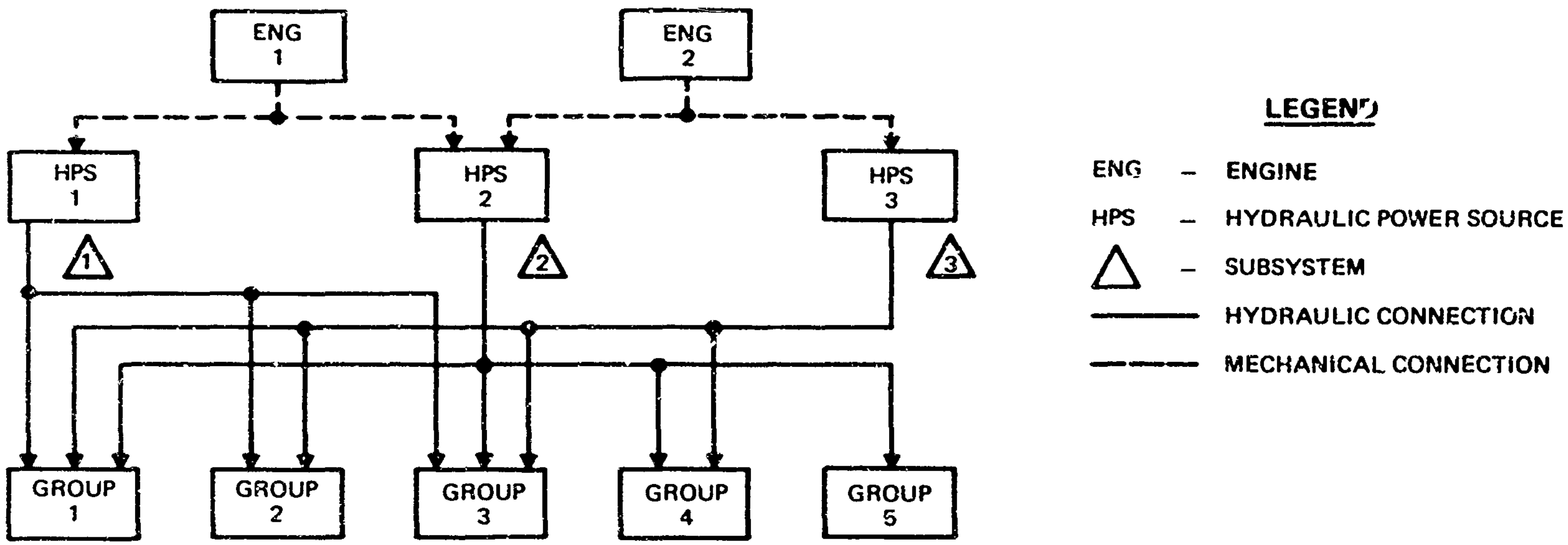

Figure 3. Block Diagram for Concept No. 2 Three Hydraulic Sources and Concept No. 3 High Pressure

subsystems without any priorities established for critical components. The area of the armorplate was established as the sum of component net areas in the front, rear, side, and bottom projections. These areas are shown below. The weight of mounting provisions was estimated at 15% of the armorplate weight. This includes bracketry and attachments in excess of existing structure. The armorplate material selected was aluminum oxide, based on consideration of weight and cost. No attempt was made in the definition phase to optimize the extent of armorplate usage.

Projection		Area (ft^2)
Side (2)		26.2
Bottom		19.8
Front and Rear		24.0
Total Area	=	70.00 ft^2

(2) Three Hydraulic Sources (Concept No. 2)

This system, shown in Figure 3, is similar to the baseline system, except the critical functions of groups 1 and 3 are shared by the three subsystems and all functions are powered by at least one of the three power sources in lieu of using emergency accumulators. Functions powered by each subsystem are shown in Table VI. Separate actuators are used by each subsystem at each function. Each subsystem is entirely independent and critical. Loss of any two subsystems places the system in the emergency mode.

(3) High Pressure Hydraulics (Concept No. 3)

This system is similar to Concept No. 2, except it is a 9000 psi system. Figure 3 and Table VI are applicable to this system. Data for defining this system were derived from Reference 1.

(4) Electromechanical Backup (Concept No. 4)

This system is shown in Figure 4 with functions and subsystems listed in Table VII. During normal operation, power for all functions is supplied by the two hydraulic sources. The electromechanical backup subsystem is automatically switched in for groups 1 and 2 functions after loss of the two hydraulic subsystems and for group 4 after loss of subsystem 2. The existing aircraft electrical generating system supplies the power for the electromechanical actuator packages. This is possible during the emergency mode, because all but the most essential demands on the generating system will be shut off. The resulting available electrical power is sufficient for the reduced requirements of the backup subsystem.

Subsystem 1 supplies fluid to a pneumatically charged brake accumulator in subsystem 3; partial independency is obtained with the use of the shutoff valve. Flaps were included for operation by the backup subsystem to reduce the critical area in subsystem 1. Subsystems 1 through 4 are critical subsystems. The system is in the emergency mode when any two of subsystems 1, 2, or 3 are lost, or when any two of

TABLE V

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 1

FUNCTION	SUBSYSTEM			
	1	2	3	4
Aileron	X	X		
UHT	X	X		
Spoiler	X	X		
Rudder	X	X		
Speed Brake		X		
Refuel		X		
Wheel Brakes	X	X		X
Landing Gear; Doors			X	X
Gear			X	
Flaps			X	X
Arresting Gear			X	
N. G. Steering			X	

TABLE VI

SUBSYSTEMS AND FUNCTIONS
CONCEPT NOS. 2 AND 3

FUNCTION	SUBSYSTEM		
	1	2	3
Aileron	X	X	X
UHT	X	X	X
Spoiler	X		X
Rudder	X		X
Speed Brake	X		X
Refuel	X		X
Wheel Brakes	X	X	X
Landing Gear: Doors	X	X	X
Gear		X	
Flaps		X	X
Arresting Gear		X	
N. G. Steering		X	

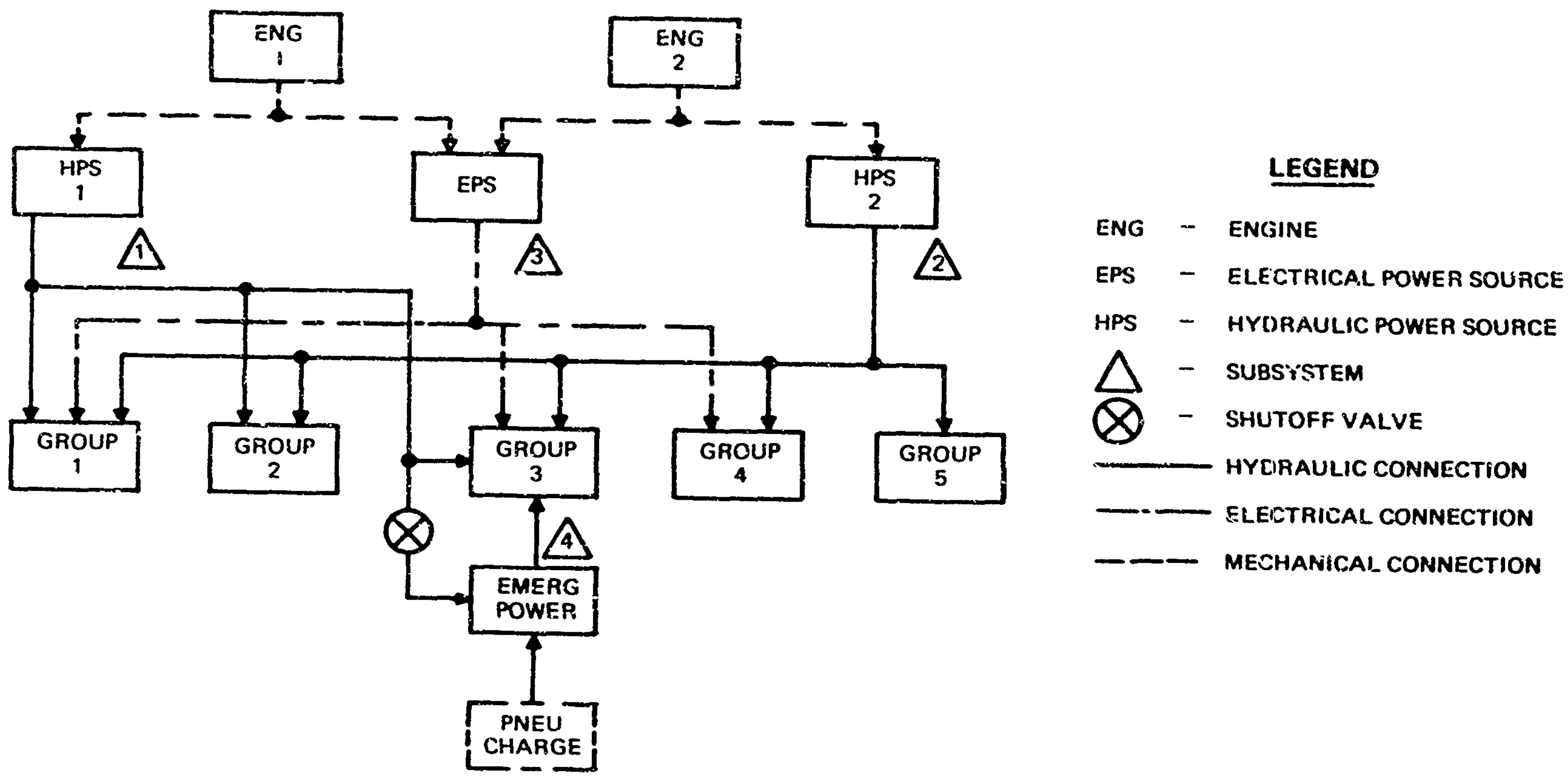

Figure 4. Concept No. 4 Electromechanical Backup Block Diagram

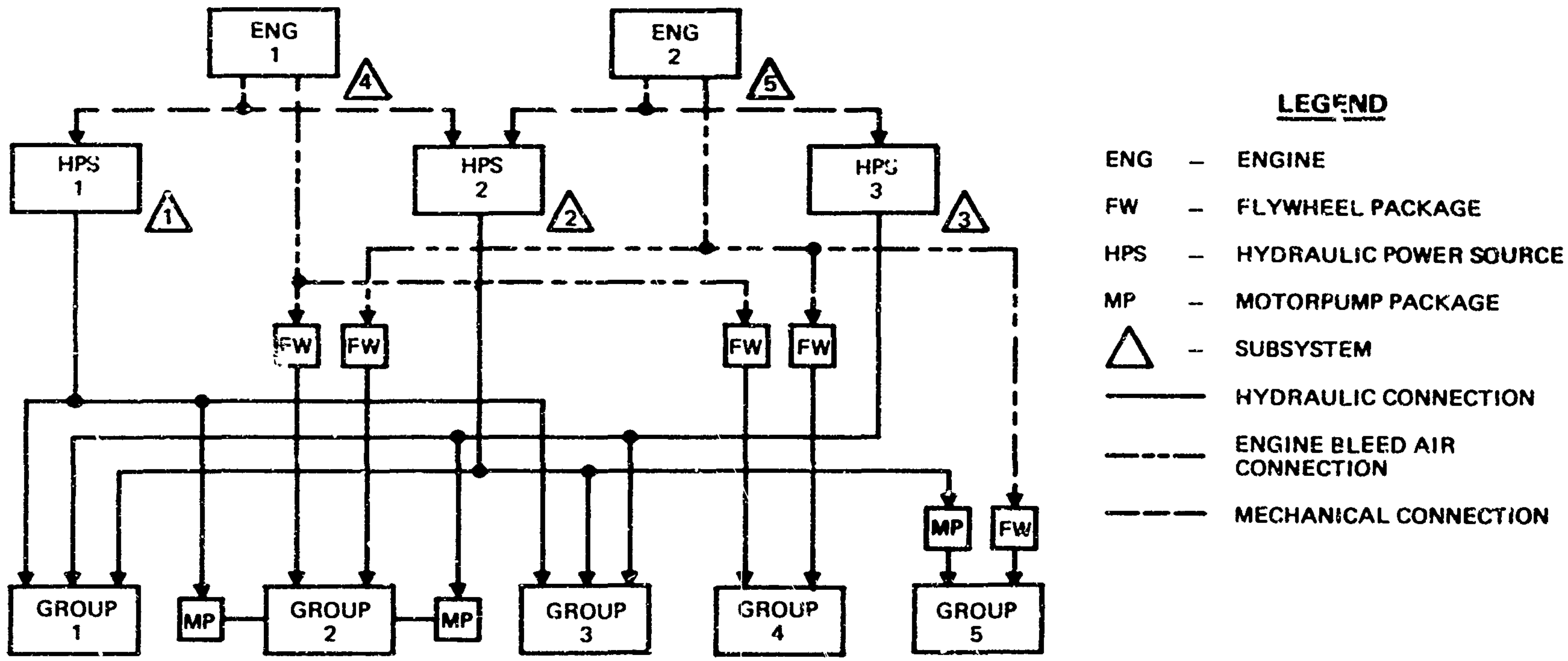

Figure 5. Concept No 5 Flywheel Power Block Diagram

subsystems 1, 2, and 4 are lost. Since electrical systems have inherent isolation, loss of the flap circuit in subsystem 3 will not affect the critical functions. Aileron trim tabs are used for control by electromechanical actuators, since load and rate requirements for the one-piece aileron are in excess of actuator capabilities.

The flight control actuators in the backup subsystem are automatically clutched in upon loss of the two hydraulic subsystems. A time lag will occur during pressure sensing and signal transmission to a clutch. The electric motors in the flight control actuators are continuously running to prevent an additional lag. The screwjacks are unloaded and free to move with the surface during normal operation.

(5) Flywheel Power (Concept No. 5)

This system is shown in Figure 5 with subsystems and functions shown in Table VIII. The three hydraulic sources, as subsystems 1, 2, and 3, power all the critical functions of groups 1 and 3 and also the rudder and spoiler of group 2 and the nose gear steering of group 5. Dividing these subsystems into major and minor circuits reduces the vulnerable or critical area of each subsystem. Thus the critical areas are the major circuits of the three hydraulic subsystems. Loss of any two places the system in the emergency mode. Loss of any minor circuit will affect the noncritical functions only. The remaining noncritical functions are isolated or separated from the critical subsystems by the use of engine bleed air as the power source. Bleed air at 90 psi and 28 SCFM provides low power to pneumatic rotary vane motors in the flywheel packages. The motor drives the flywheel which stores up energy to drive a hydraulic pump. The functions selected for flywheel power do not require continuous operation; sufficient time occurs between half cycles to permit energy buildup. Isolating the speed brake from the functions required for the maximum power operating condition, paragraph 2b of this section, reduces the power drain on the engines.

(6) Electrohydraulic Backup (Concept No. 6)

This system is shown in Figure 6 with subsystems and functions shown in Table IX. This system is similar to Concept No. 4, except that electrical power is converted into hydraulic power for backup. Loss of the two hydraulic subsystems will automatically direct pump flow from the motorpump package in subsystem 3 to the flight control actuators. Subsystem 3 has only one minor circuit; its loss has no effect on the critical functions. The inherent isolation of electrical systems allows the loss of single critical functions.

The time lag for Concept No. 4 is also to be considered for this system. The difference would be in the response of the motor-pump circuit compared to that for the electromechanical actuator. The hydraulic actuators in the backup subsystem must have provisions for bypassing fluid to allow free motion of the actuator when not in use.

TABLE VII

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 4

FUNCTION	SUBSYSTEM			
	1	2	3	4
Aileron	X	X	X	
UHT	X	X	X	
Spoiler	X	X		
Rudder	X	X		
Speed Brake	X	X		
Refuel	X	X		
Wheel Brakes	X	X		X
Landing Gear: Doors	X	X	X	
Gear		X		
Flaps		X	X	
Arresting Gear		X		
N. G. Steering		X		

TABLE VIII

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 5

FUNCTIONS	SUBSYSTEM				
	1	2	3	4	5
Aileron	M	M	M		
UHT	M	M	M		
Spoiler	m		m		
Rudder	m		m		
Speed Brake				m	m
Refuel				m	m
Wheel Brakes	M	M	M		
Landing Gear: Doors	M	M	M		
Gear					m
Flaps				m	m
Arresting Gear					m
N. G. Steering		m			

M - major circuit in subsystem

m - minor circuit in subsystem

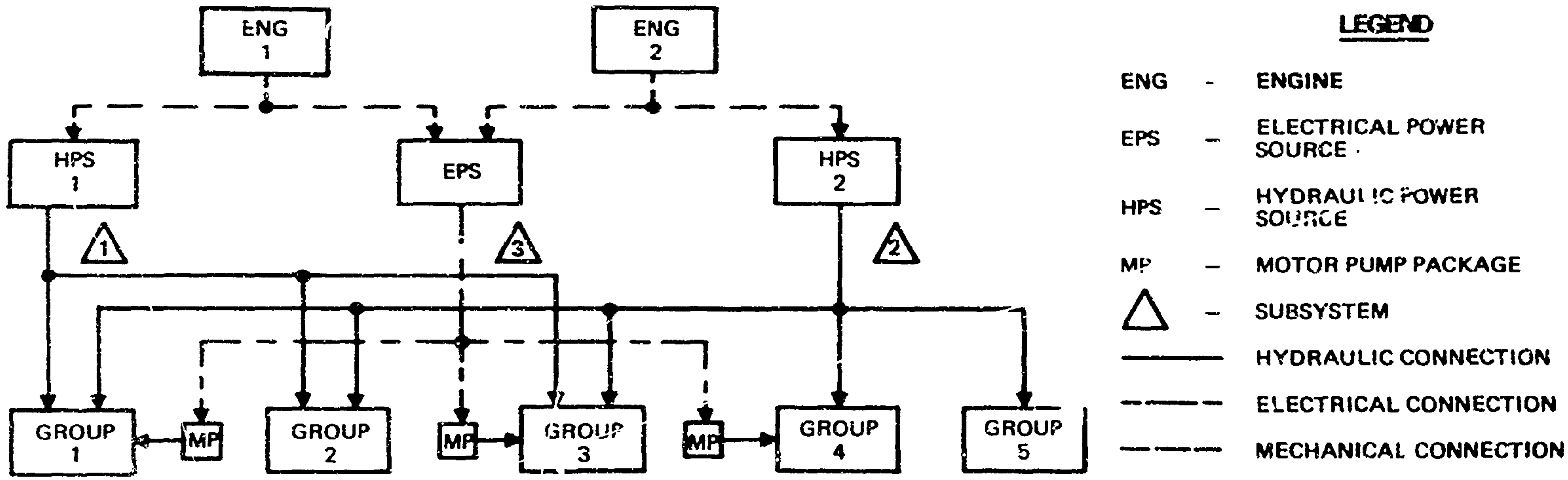

Figure 6. Concept No. 6 Electrohydraulic Backup Block Diagram

TABLE IX

SUBSYSTEMS AND FUNCTIONS
CONCEPT NO. 6

FUNCTION	SUBSYSTEM 1	SUBSYSTEM 2	SUBSYSTEM 3
Aileron	X	X	M
UHT	X	X	M
Spoiler	X	X	
Rudder	X	X	
Speed Brake	X	X	
Refuel	X	X	
Wheel Brakes	X	X	M
Landing Gear: Doors	X	X	M
Landing Gear: Gear		X	
Flaps		X	m
Arresting Gear		X	
N.G. Steering		X	

M - Major circuit in subsystem

m - Minor circuit in subsystem

X - Total subsystem

(7) Five Hydraulic Sources (Concept No. 7)

This system is shown in Figure 7 with subsystems and functions shown in Table X. The system is similar to Concept No. 2 with two additional power sources and subsystems. This system represents maximum separation of critical and noncritical functions. This is accomplished by providing separate power sources. Loss of any two of the subsystems 1, 3, or 4 will place the system in the emergency mode.

(8) Pulsating Flow (Concept No. 8)

This system is shown in Figure 8 with subsystems and functions shown in Table XI. System design utilized information in Reference 2. Three conventional hydraulic power sources provide fluid under pressure to three alternators which convert the fluid to three-phase pulsating or alternating flow. The alternators are driven by hydraulic motors and are mechanically synchronized. The pulsating flow fluid from all three alternators is combined in three transmission lines (each transmitting one phase) for power distribution. Rectifier valves convert the pulsating flow to continuous flow at the actuators. Transformers with 1:1 area ratios are used to isolate each actuator and alternator in each of the three phases or transmission lines. Three-phase rectified flow is used for all flight control actuators and nose gear steering. Two-phase rectified flow is used for speed brake and refuel, and single-phase is used for the remaining functions. Each flap surface is driven by three actuators, each powered by a different phase of the three-phase circuit.

Each power source to the alternator is identified as a subsystem. These are critical subsystems (1, 2, 3) in that loss of any two subsystems places the system in the emergency mode. The pulsating flow portion of the system (including actuators) is divided into three critical subsystems (4, 5, 6). These subsystems are further divided into major and minor circuits; these are identified by functions in Table XI. Both critical and noncritical actuators are isolated from subsystems 4, 5, and 6; however, only the noncritical actuators are in the minor circuits. Loss of any two pulsating flow subsystems (4, 5, 6) upstream of transformers at the actuators will place the system in the emergency mode. Further, loss of any two major circuits (actuators) for a function will place the system in the emergency mode. All actuators are isolated such that a single failure (actuator) can occur without affecting other actuators.

(9) Electrohydraulic Power Package (Concept No. 9)

This system is shown in Figure 9 with subsystems and functions shown in Table XII. This system was designed to make maximum use of electrical power and electrical transmission. Power for all functions is supplied by the three electrical power generators which are separate from the aircraft primary electrical sources. The electrical power is converted into hydraulic power by the electrohydraulic power packages. Each package contains one to three units, each containing an electric motor, hydraulic pump, reservoir, and filter. Seventeen motor-pump units are used to power all functions. Each unit powers single

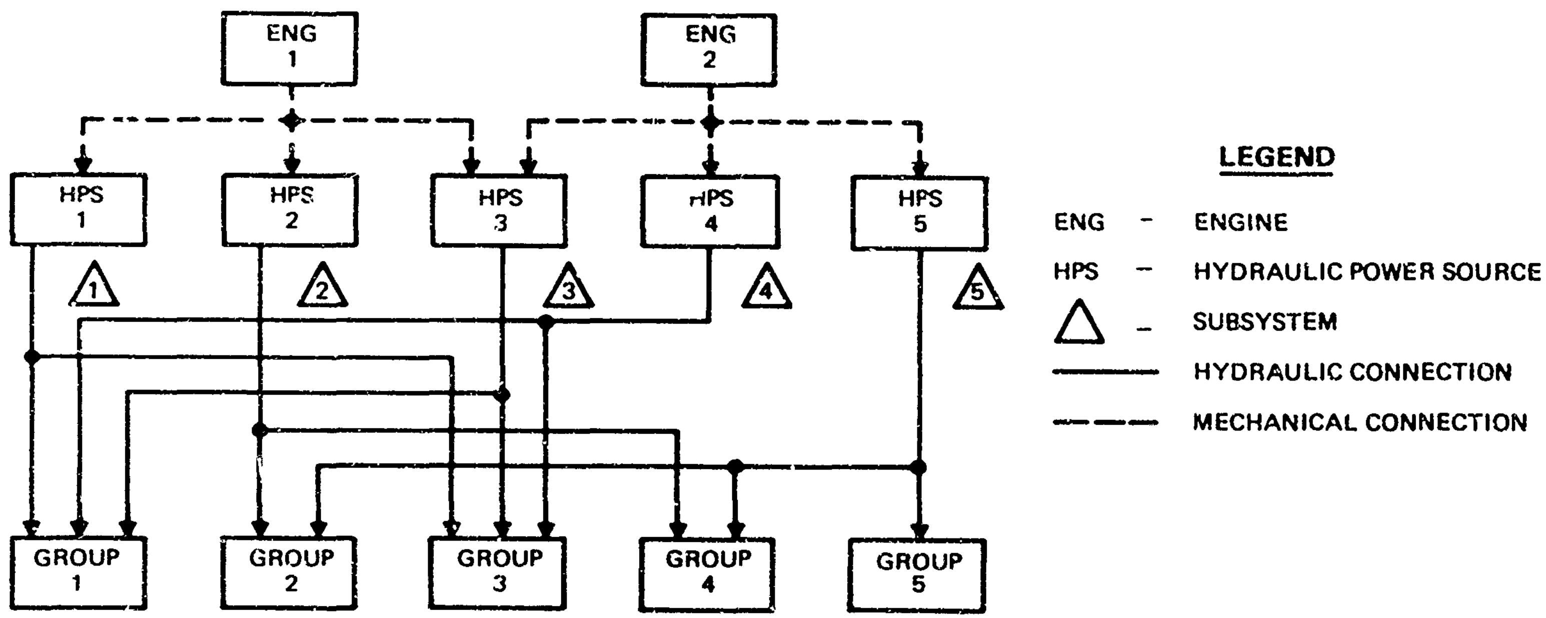

Figure 7. Concept No. 7 Five Hydraulic Sources Block Diagram

TABLE X

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 7

FUNCTION	SUBSYSTEM				
	1	2	3	4	5
Aileron	X		X	X	
UHT	X		X	X	
Spoiler		X			X
Rudder		X			X
Speed Brake		X			X
Refuel		X			X
Wheel Brakes	X		X	X	
Landing Gear: Doors Gear	X		X	X	
Flaps		X			X
Arresting Gear					X
N. G. Steering					X

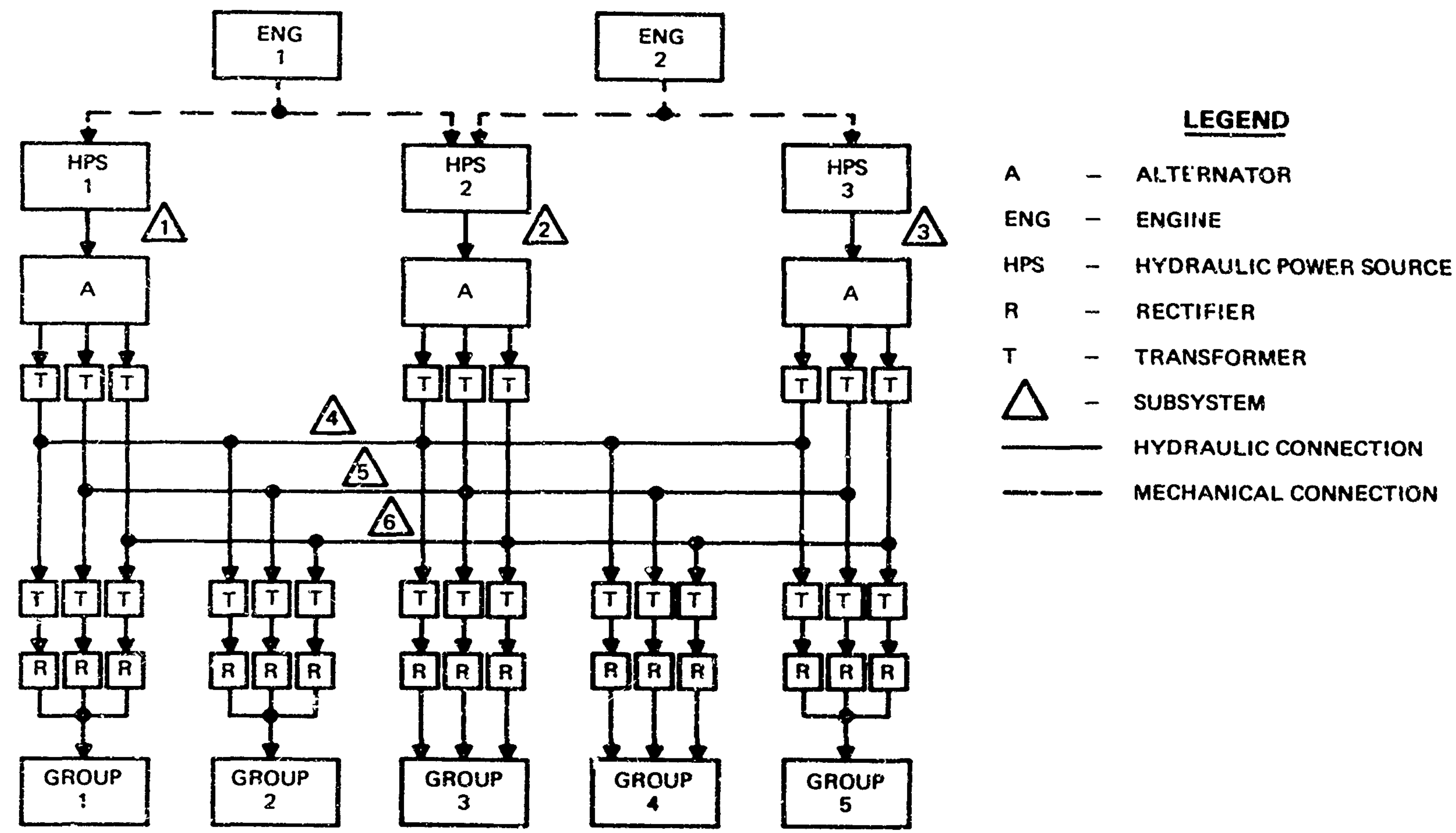

Figure 8. Concept No. 8 Pulsating Flow Block Diagram

TABLE XI

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 8

FUNCTION	SUBSYSTEM					
	1	2	3	4	5	6
Aileron	X	X	X	M	M	M
UHT	X	X	X	M	M	M
Spoiler	X	X	X	m	m	m
Rudder	X	X	X	m	m	m
Speed Brakes	X	X	X		m	m
Refuel	X	X	X		m	m
Wheel Brakes	X	X	X	M	M	M
Landing Gear: Doors	X	X	X	M	M	M
Gear	X	X	X	m		
Flaps	X	X	X	m	m	m
Arresting Gear	X	X	X	m		
N. G. Steering	X	X	X	m	m	m

M - Major Circuit of Subsystem

m - Minor Circuit of Subsystem

X - Total Subsystem

functions or multiple functions as shown on Table XII. The number of these units was based on a practical arrangement considering both aircraft physical limitations and electrical load distribution.

The electrical subsystems 1, 2, and 3 inherently isolate all functions; i.e., the loss of any one function will not affect another function in the subsystem. The degree of isolation is also dependent on the arrangement of the electrical distribution s systems. The loss of any two of the electrical subsystems adjacent to the generators, or in the generators, will place the system in the emergency mode. In this system the hydraulic circuits are considered major and minor circuits of the subsystems 1, 2, and 3. The loss of any two major circuits powering a critical function will place the system in the emergency mode. There are three major circuits for each of the four critical functions.

(10) Motorpump Isolation (Concept No. 10)

This system is shown in Figure 10 with subsystems and functions shown in Table XIII. It is similar to Concept No. 2, except motorpump packages are added to isolate noncritical functions from the critical functions. These noncritical functions become part of the minor circuits in the three subsystems. Loss of any two major circuits in subsystems 1, 2, or 3 places the system in the emergency mode.

(11) Automatic Failure Isolation (Concept No. 11)

This system is shown in Figure 11 with subsystems and functions shown in Table XIII. It is similar to Concept No. 10, except automatic failure isolation (AFI) packages are used in place of motorpumps. Greater isolation is accomplished by separating left-hand and right-hand noncritical functions with the use of 17 isolation packages; ten motorpumps were used for isolation on Concept No. 10.

The AFI packages automatically detect and isolate minor circuits which experience fluid loss resulting from battle damage. In principle, the packages will continuously monitor the fluid conditions (flow or pressure). Any change from acceptable conditions will be detected and compared. If an unacceptable condition occurs, a valve will be activated to shut off fluid supply and return lines, thus isolating the circuit downstream of the AFI package.

AFI can be accomplished by electrical or mechanical (hydraulic) methods. With the system definition at a conceptual level, the particular method for AFI may not be important. The method selected to support system definition utilizes flow sensors in the fluid supply and return lines. These sensors transmit electrical signals proportional to flow to a control logic for comparison. Under normal conditions, flow in both lines should be within a range which accounts for pressure surges and environmental effects. An open line will create a flow differential which will be known at the control logic. A signal is then transmitted to energize a shutoff or selector valve to isolate the damaged hydraulic circuit. Loss of any two major circuits in subsystems 1, 2, or 3 places the system in the emergency mode.

TABLE XII

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 9

FUNCTION	SUBSYSTEM 1	SUBSYSTEM 2	SUBSYSTEM 3
Aileron	X	X	X
UHT	X	X	X
Spoiler	X(1)		X(1)
Rudder	X		X
Speed Brake	X		X(2)
Refuel		X(1)	X(2)
Wheel Brakes	X(2)	X(3)	X(3)
Landing Gear: Doors	X(2)	X(3)	X(3)
Main Gear		X(2)	
Nose Gear			X(2)
Flaps	X(1)		X(1)
Arresting Gear		X(2)	
N. G. Steering		X(1)	

Number in parentheses designates functions powered by a common motorpump.

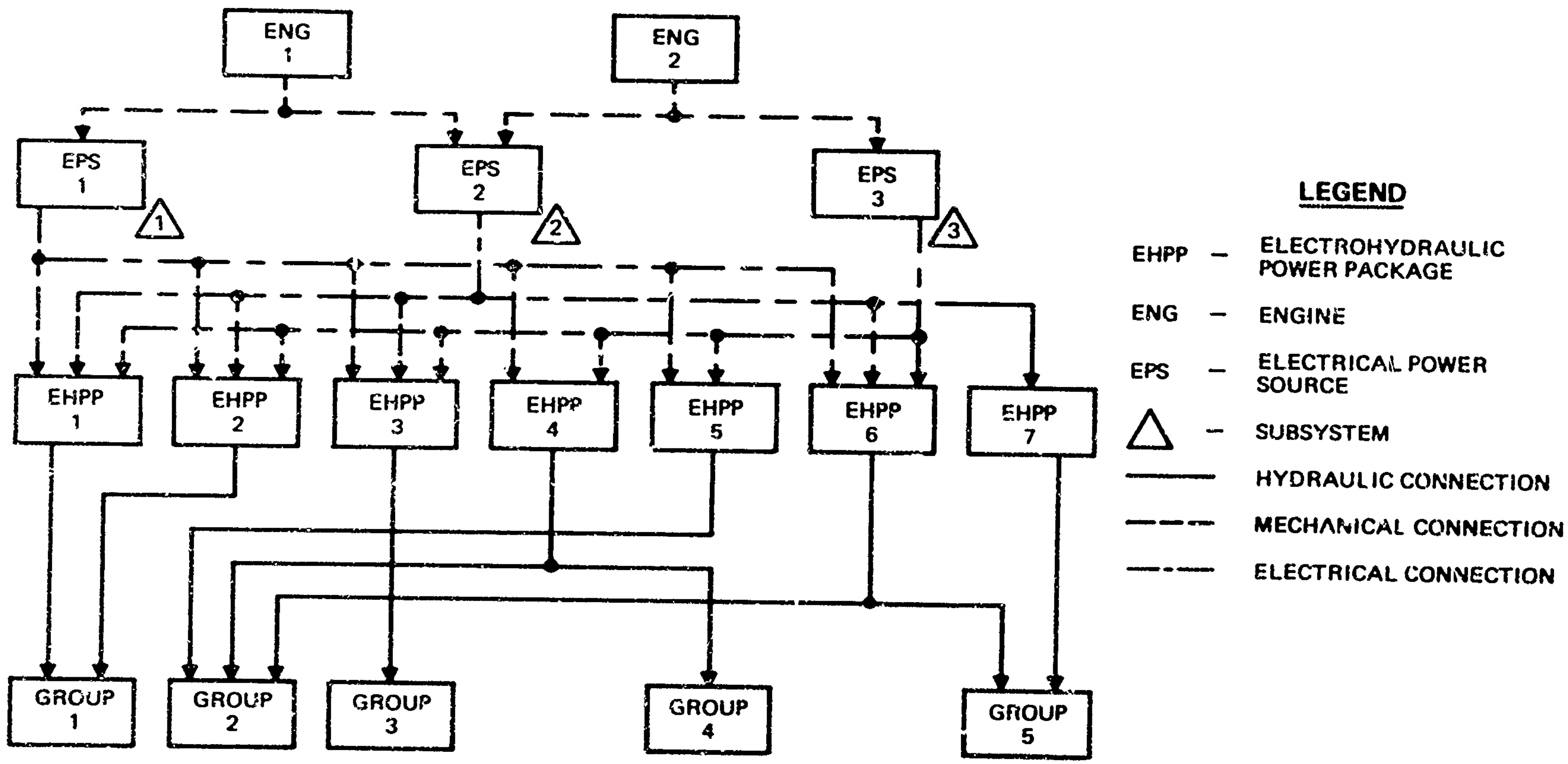

Figure 9. Concept No. 9 Electrohydraulic Power Package Block Diagram

TABLE XIII

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 10 AND NO. 11

FUNCTION	SUBSYSTEM		
	1	2	3
Aileron	M	M	M
UHT	M	M	M
Spoiler	m		m
Rudder	m		m
Speed Brake	m		m
Refuel	m		m
Wheel Brakes	M	M	M
Landing Gear: Doors	M	M	M
Gear		m	
Flap		m	m
Arresting Gear		m	
N. G. Steering		m	

M - Major circuits in subsystem

m - minor circuits in subsystem

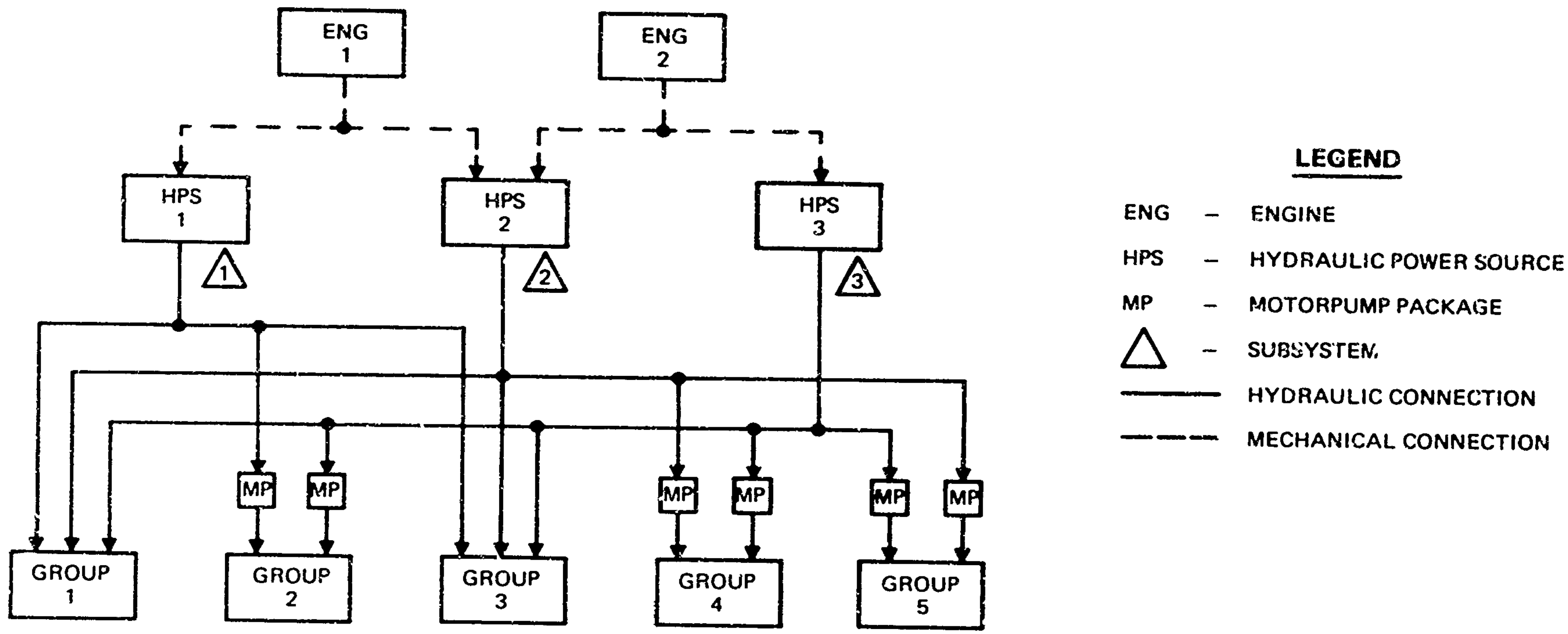

Figure 10. Concept No. 10 Motorpump Isolation Block Diagram

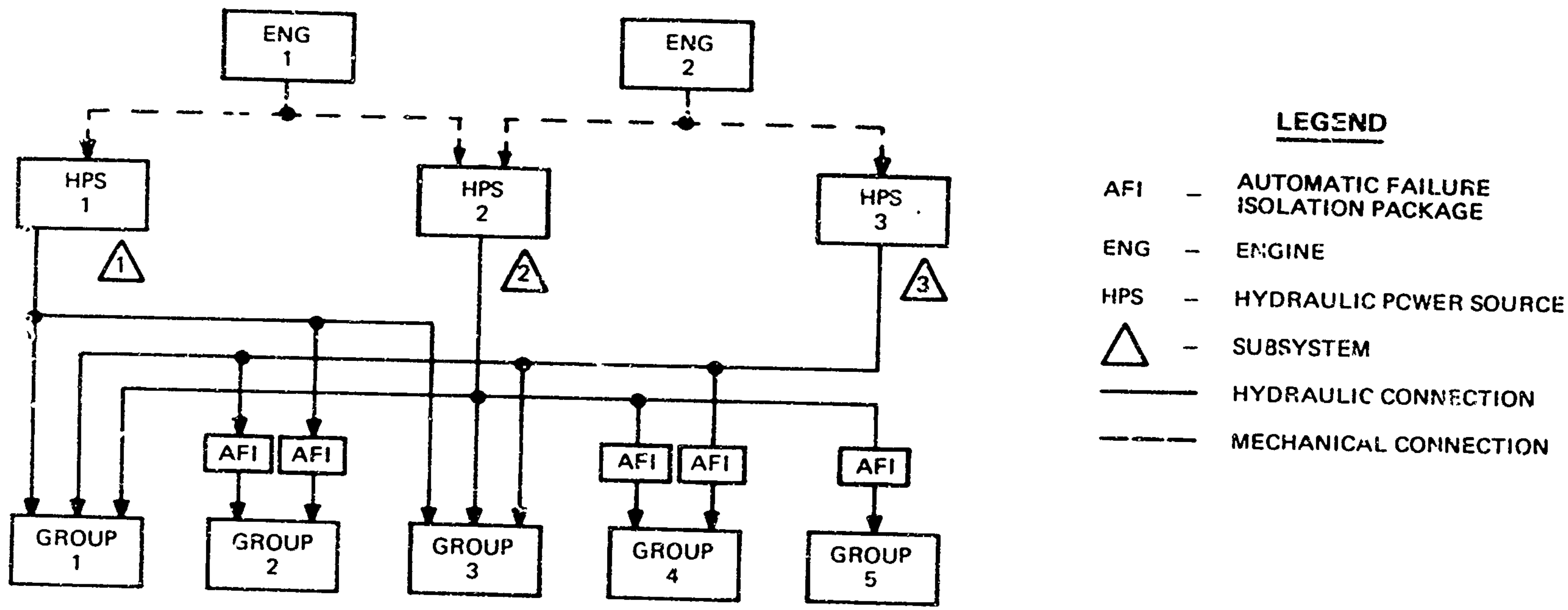

Figure 11. Concept No. 11 A omatic Failure Isolation Block Diagram

d. Modified Systems

(1) Modified Pulsating Flow (Concept No. 8A)

This system is shown in Figure 12 with subsystems and functions shown in Table XIV. It is similar to Concept No. 8, except that functions are combined in the rectified circuits according to criticality. This was accomplished to reduce the number of transformers used on Concept No. 8, recognizing that the degree of isolation would also be reduced.

The pulsating flow subsystems 4, 5, and 6 are divided into the same major and minor circuits. Three-phase flow is rectified into separate conventional flow circuits to each aileron and UHT actuator and into two separate circuits for all noncritical functions. Single-phase flow is rectified for each door and brake circuit. The system is placed in the emergency mode under similar failure conditions as for Concept No. 8. Since isolation has been reduced, loss of one function (actuator) will affect other functions.

(2) Modified Pulsating Flow (Concept No. 8B)

This system is shown in Figure 13, with subsystems and functions shown in Table XV. It is similar to Concept No. 8A, except that only the critical functions utilize pulsating flow. Two additional hydraulic power sources provide conventional flow directly to the noncritical functions. These subsystems are identical to subsystems 2 and 5 of Concept No. 7 shown in Figure 7. The system is placed in the emergency mode when any two of the subsystems 4, 5, or 6 are lost.

(3) Modified Electrohydraulic Power Package (Concept No. 9A)

This system is shown in Figure 14 with subsystems and functions shown in Table XVI. It is similar to Concept No. 9, except electrohydraulic power packages provide power to the critical functions only. Two hydraulic power sources and subsystems are added to power the noncritical functions. These subsystems are identical to subsystems 2 and 5 of Concept No. 7, Figure 7. The system is placed in the emergency mode when any two of the subsystems 1, 2, or 3 sustain failure in or near the generators. This mode will also occur when any two major circuits (hydraulics) powering a critical function are lost.

4. SUMMARY DATA

Significant data relating all the systems are tabulated in Tables XVII, XVIII, and XIX. Table XVII lists types of components and indicates the commonality across all the systems. Physical data of each system are tabulated in Table XVIII. This table describes and relates system size in terms of component quantities, length of transmission lines, and system volumes for both critical and noncritical portions of the system. Volume of transmission lines accounts for 10 to 20% of the total system volume. Flow requirements to each actuator per subsystem are shown in

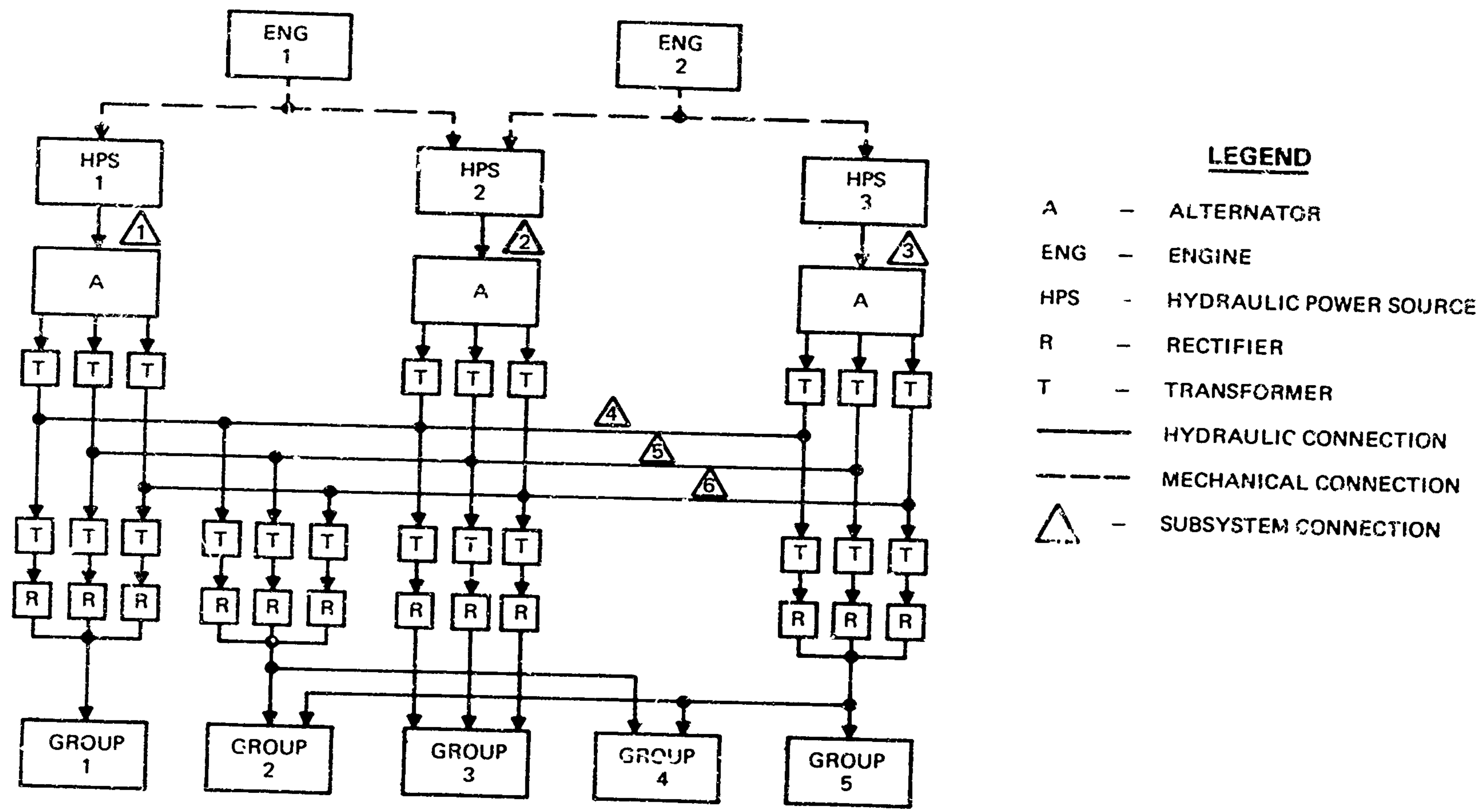

Figure 12. Concept No. 8A Pulsating Flow (Modified) Block Diagram

TABLE XIV

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 8A

FUNCTION	SUBSYSTEM					
	1	2	3	4	5	6
Aileron	X	X	X	M	[illegible]	M
UHT	X	X	X	M	M	M
Spoiler	X	X	X	m	m	m
Rudder	X	X	X	m	m	m
Speed Brake	X	X	X	m	m	m
Refuel	X	X	X	m	m	m
Wheel Brakes	X	X	X	M	M	M
Landing Gear: Doors	X	X	X	M	M	M
Landing Gear: Gear	X	X	X	m	m	m
Flaps	X	X	X	m	[illegible]	m
Arresting Gear	X	X	X	m	m	m
N. G. Steering	X	X	X	m	m	m

M - Major circuit of subsystem

m - Minor circuit of subsystem

X - Total subsystem

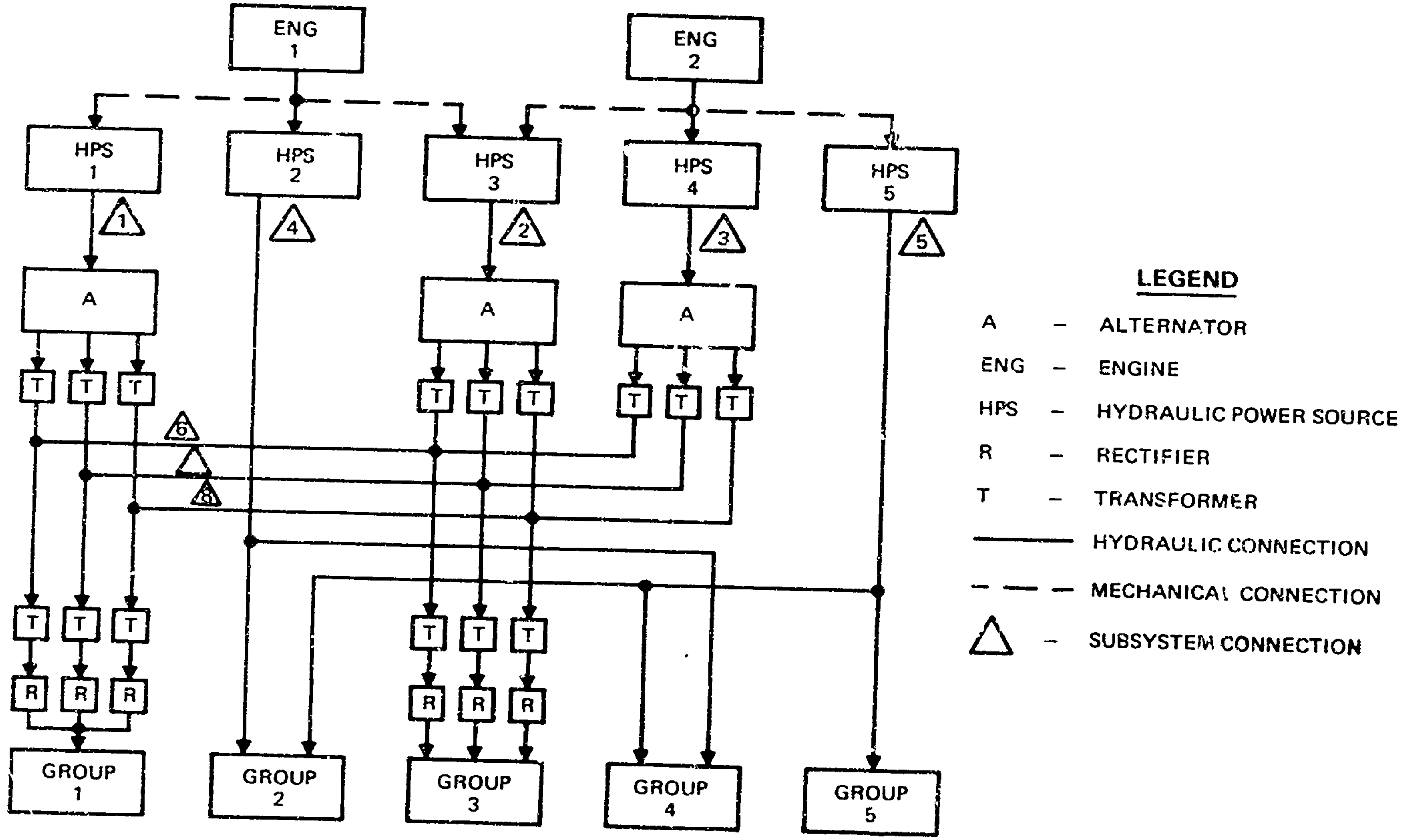

Figure 13. Concept No. 8B Pulsating Flow (Modified) Block Diagram

TABLE XV

SUBSYSTEMS AND FUNCTIONS - CONCEPT NO. 8B

FUNCTION	SUBSYSTEM							
	1	2	3	4	5	6	7	8
Aileron	X	X	X			X	X	X
UHT	X	X	X			X	X	X
Spoiler	X	X	X	X	X			
Rudder	X	X	X	X	X			
Speed Brake	X	X	X	X	X			
Refuel	X	X	X	X	X			
Wheel Brakes	X	X	X			X	X	X
Landing Gear: Doors	X	X	X			X	X	X
Gear	X	X	X		X			
Flaps	X	X	X	X	X			
Arresting Gear	X	X	X		X			
N. G. Steering	X	X	X		X			

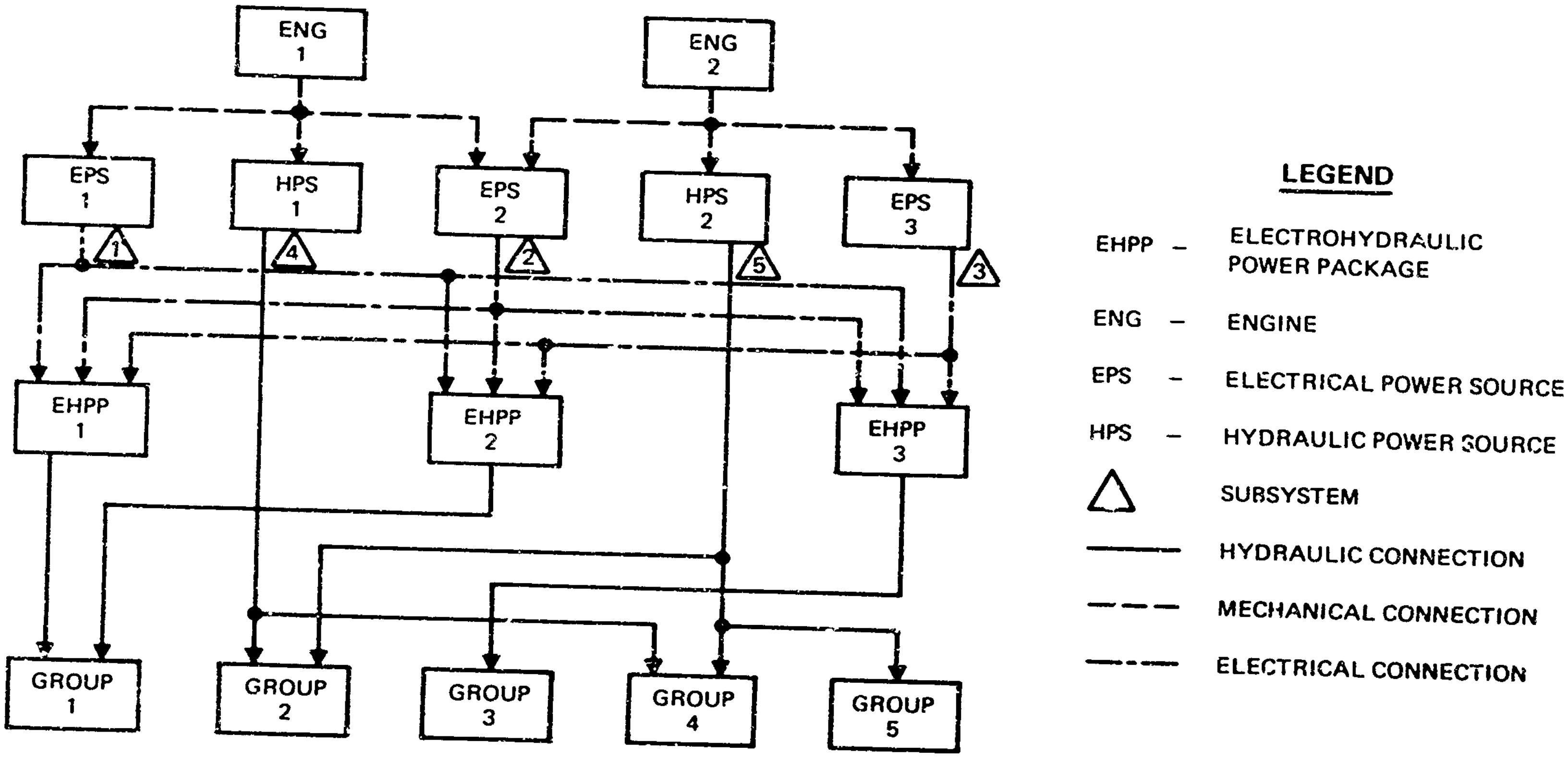

Figure 14. Concept No. 9A Electrohydraulic Power Package (Modified) Block Diagram

TABLE XVI

SUBSYSTEMS AND FUNCTION - CONCEPT NO. 9A

FUNCTION	SUBSYSTEM				
	1	2	3	4	5
Aileron	X	X	X		
UHT	X	X	X		
Spoiler				X	X
Rudder				X	X
Speed Brake				X	X
Refuel				X	X
Wheel Brakes	X	X	X		
Landing Gear: Doors	X	X	X		
Gear					X
Flaps				X	X
Arresting Gear					X
N. G. Steering					X

Table XVII. Component Usage

COMPONENT	QUANTITY OF COMPONENT ON CONCEPT NO.													
	1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
ACCUMULATOR	7	4	4	3	4	2	6	4	4	6		2	4	4
ACTUATOR														
ELECTROMECHANICAL				17										
HYDRAULIC	34	56	56	39	56	56	56	54	56	56	56	56	56	56
ALTERNATOR, HYDRAULIC								3	3	3				
AFI PACKAGE														18
BRAKE VALVES	2	6	6	4	6	4	6	6	6	6	6	6	6	6
FILTER	8	8	8	4	8	4	12	8	8	12		4	8	8
FLYWHEEL PACKAGE					5									
GENERATOR											3	3		
MOTORPUMP, ELECTRICAL						4					17	9		
MOTORPUMP, HYDRAULIC					5								10	
PUMP	4	4	4	2	4	2	6	4	4	6		2	4	4
RECTIFIER, HYDRAULIC									11	9				
RESERVOIR	3	3	3	2	3	2	5	3	3	5		2	3	3
SELECTOR VALVE, ELECTRICAL	3	5	5	5	5	5	5		5	5	5	5	5	
SELECTOR VALVE, MANUAL	6	5	5	5	6	4	6		6	6	7	6	6	3
TRANSFORMER, HYDRAULIC								84	36	30				
TOTAL	67	91	91	81	102	83	102	166	142	144	94	95	102	102

Table XVIII. System Physical Data

PARAMETER	CONCEPT NUMBER														
	1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
(1) NUMBER OF COMPONENTS															
CRITICAL	67	67	91	91	71	54	72	49	133	91	89	42	42	59	67
NONCRITICAL	-	-	-	-	10	48	11	53	33	51	55	52	53	43	35
TOTAL	67	67	91	91	81	102	83	102	166	142	144	94	95	102	102
(2) LINE LENGTH (FEET)															
TUBING	956	956	1211	1194	707	1782	856	1437	1045	1605	1605	1115	1301	1528	1150
WIRING	-	-	-	-	217	-	-	-		-	-	1166	601	-	-
TOTAL	956	956	1211	1194	924	1782	856	1437	1045	1605	1605	2281	1902	1528	1150
(3) SYSTEM VOLUME (CU. FT.)															
CRITICAL VOLUME	10.15	1.80	11.70	7.18	11.10	9.60	10.65	6.82	8.89	9.30	9.25	11.22	11.22	10.73	8.92
NONCRITICAL VOLUME	0	8.35	0	0	3.31	5.24	1.96	6.27	4.20	4.54	11.60	8.72	6.30	3.82	3.78
TOTAL	10.15	10.15	11.70	7.18	14.41	14.84	12.61	13.09	13.09	13.84	20.85	19.94	17.52	14.55	12.70

Table XIX. Differences in flow requirements are attributed to the use of single or tandem actuators and the higher pressure. The pump size for subsystem 1 of Concept No. 2 (Figure 3), for example, is determined by multiplying the sum of the flows for the actuators in groups 1 and 2 (first five functions in Table VI) by 60%. The required pump flow is then 54 gpm, neglecting system efficiency. A further breakdown of component and system physical and performance data is shown in Appendix I.

TABLE XIX

ACTUATOR FLOW REQUIREMENTS

FUNCTION	ACTUATOR FLOW REQUIREMENTS - (GPM)		
	Concepts Nos. 1 and 4	Concept No. 3	Remaining Concepts
Aileron	*16.6	3.7	11.0
UHT	*13.6	3.0	9.0
Spoiler	11.0	3.7	11.0
Rudder	7.6	2.5	7.6
Speed Brake	42.0	7.0	20.6
Refuel	0.6	0.2	0.6
Brakes	0.6	0.2	0.6
Landing Gear:			
Doors(N.G./M.G.)	*0.5/1.4	0.2/0.5	0.5/1.4
Gear(N.G./M.G.)	3.0/1.6	1.0/0.5	3.0/1.6
Flaps			
L.E. (Outbrd/Inbrd)	*0.5/1.0	0.2/0.3	0.5/1.0
T.E.	*0.5	0.2	0.5
Arresting Gear	3.5	1.2	3.5
N.G. Steering	4.4	1.5	4.4

* Concept No. 1 only

SECTION VII

SYSTEM EVALUATION

1. INTRODUCTION

The definitions in Section VI emphasized a search for systems more survivable than the baseline system through the reduction of vulnerable areas by increased redundancy, isolation, and backup methods and by the addition of armorplate. These systems were then evaluated regarding vulnerability/survivability, reliability, maintainability, weight, performance, and system cost. The objective was to derive parameters for a cost analysis (i.e., probability of survival, reliability, MTBF, etc.) and to assign rating values by each area for each system. Each area used conventional or specially developed methods of evaluation. These methods required assumptions beyond the system definition; such assumptions were based on experience and sound judgment. Service data from VAD operational aircraft were used in the evaluation. The cost parameters and rating values were used for cost rating and value rating, discussed in Sections VIII and IX, respectively.

a. Vulnerability/Survivability

This evaluation considered the net projected or vulnerable area and the number of subsystems within this area. Vulnerable area is the total projected area of all components and transmission lines in the critical subsystems.

b. Reliability

This evaluation determined the probability of mission completion neglecting failures by battle damage. Each system was evaluated on a component level, considering failure rates, failure modes, and the effect of these failures on total system operation.

c. Maintainability

Maintainability evaluation was based on a number of factors including reliability, equipment replacement rates, equipment location, accessibility to the equipment, special maintenance requirements and techniques, etc.

d. Weight

Standard weight estimating techniques used in the aircraft industry were employed.

e. Performance

Each system was designed to provide the required performance in the normal mode of operation. This evaluation considered the degradation of airplane and system performance after sustaining certain losses.

f. Cost

Cost data were extrapolated from cost information on similar equipment, from vendor information, and from experience in hardware development.

2. VULNERABILITY/SURVIVABILITY

a. Vulnerability Analysis

(1) Introduction

The objective of the vulnerability analysis was to identify the critical subsystems within each hydraulic system and to assess the respective vulnerable areas. Design philosophy was such that each hydraulic system must have the ability to withstand or absorb two hits before being placed in an emergency mode. The analysis, therefore, was concerned primarily with those critical functions and subsystems which, if lost, would contribute to the loss of the aircraft. These functions were defined in Section IV as UHT, aileron, landing gear, and brakes. Subsystems associated solely with noncritical functions were of no significance in terms of their vulnerable areas. They were considered, however, for any protection (shielding) which was provided for critical subsystems. Subsystems which transmit power to both critical and noncritical functions were considered as vulnerable in their entirety, unless the noncritical functions were isolated.

Aircraft mission and flight profile did not have any direct influence on the vulnerability analysis. By assuming all critical components as vulnerable, except for possible shielding, each hydraulic system was evaluated in its most critical environment. Although vulnerability studies are generally related to flight profiles, it was in the best interest of this study not to limit the analysis to a specified profile.

(2) Threat

All unarmored components in the hydraulic system were considered vulnerable to the .50 cal. AP threat. At the maximum effective hitting range of 1,000 yards, the projectile velocity of 1,750 feet per second is sufficiently high to inflict severe damage on the components

based on V_{50} limits for the material types and thicknesses encountered. Thus the hydraulic system was evaluated when subjected to its most severe threat. System damage and kill philosophy were defined in order to assess hit effects and to define vulnerable areas. The fire/explosion hazard was not considered in the analysis, although it is a definite threat to the hydraulic system. Any consideration of fire or explosion would require a well-defined aircraft and would be highly influenced by the internal arrangement of the aircraft.

(3) Kill Conditions

An essential consideration in a vulnerability analysis is the effect of projectiles impacting in a critical subsystem. Conditional kill probability should be established, and an analysis of compound damage and multiple hit effects should be conducted.

(a) Conditional Kill Probability

Conditional kill probability (probability of kill given a hit) was assumed to equal unity. Although it is possible to inflict only minor damage to a hydraulic system with a .50 cal. AP projectile, the majority of components in a hydraulic system are vulnerable to projectiles whose striking velocity is greater than 1,750 feet per second (or 1,000 yards range). By assuming a component (subsystem) is killed if hit, the system is evaluated for the most severe condition of the stated threat. This method of analysis is advantageous in that it is independent of a specific flight profile or gun-to-target range. Although the profile and range are important factors in the survivability of an aircraft, they tend to limit the scope of a study (particularly when the objective is to compare the relative worth of several system concepts).

(b) Compound Damage

Compound damage was not considered. That is, each projectile impacting in a critical subsystem can kill only that subsystem. Although it is conceivable that a .50 cal. AP projectile could damage or kill several components (not necessarily in the same subsystem), the extent of compound damage would be difficult to assess. An analysis of this type would require a well-defined aircraft and would be subject to a high degree of estimation.

(c) Multiple Hits

Effects of multiple hits on a subsystem were not considered. It was assumed that the first hit kills the subsystem; hence additional hits in that subsystem had no effect on the survivability of the aircraft.

(4) Method of Analysis

The vulnerable areas of each system were analyzed using projection planes as defined by five aspect or gun-to-target angles. The aircraft orientation for each of these angles is shown in Figure 15. The aspect angles were selected in an arbitrary manner and were intended to be representative of the gun-to-target angles encountered in a combat environment. The probability of hit from each of the aspect angles was assumed to be equally likely. Projectile hits on the top surface of the aircraft were not considered, because of the limited exposure of this surface to ground fire on any engagement. Detailed analysis of combat damage reports indicated relatively few hits on the top surface.

(a) Projected Area

Components were located in a three-axis coordinate system to facilitate projected area determinations. The total projected area of each component was determined by analytical means for each angle defined in Figure 15. Using the coordinates of each component, these areas were projected along each angle to determine net projected areas by graphic means. These net projected areas accounted for shielding effects provided by the engine, fuel cells, and other components in the system. The net projected areas were divided into critical areas (areas of subsystems required to perform critical functions) and non-critical areas (areas of remaining subsystems).

The net projected areas of each critical subsystem were determined by summing the net areas of each of the critical components. These areas represented the result of the vulnerability analysis and were used in the survivability analysis. These net projected or vulnerable areas are summarized in Table XX. An example of projected or vulnerable area analysis is included in Appendix II.

b. Survivability Analysis

(1) Introduction

The objective of this analysis was to determine the survivability of each of the hydraulic systems and establish a method for comparing these systems. Each system was evaluated by using the probability of survival as a measure of effectiveness. The analysis was related directly to the vulnerable areas of each system. Probability of survival methodology required the following inputs:

(a) Number of hits in system

(b) Probability of hit in each subsystem

(c) System kill criteria.

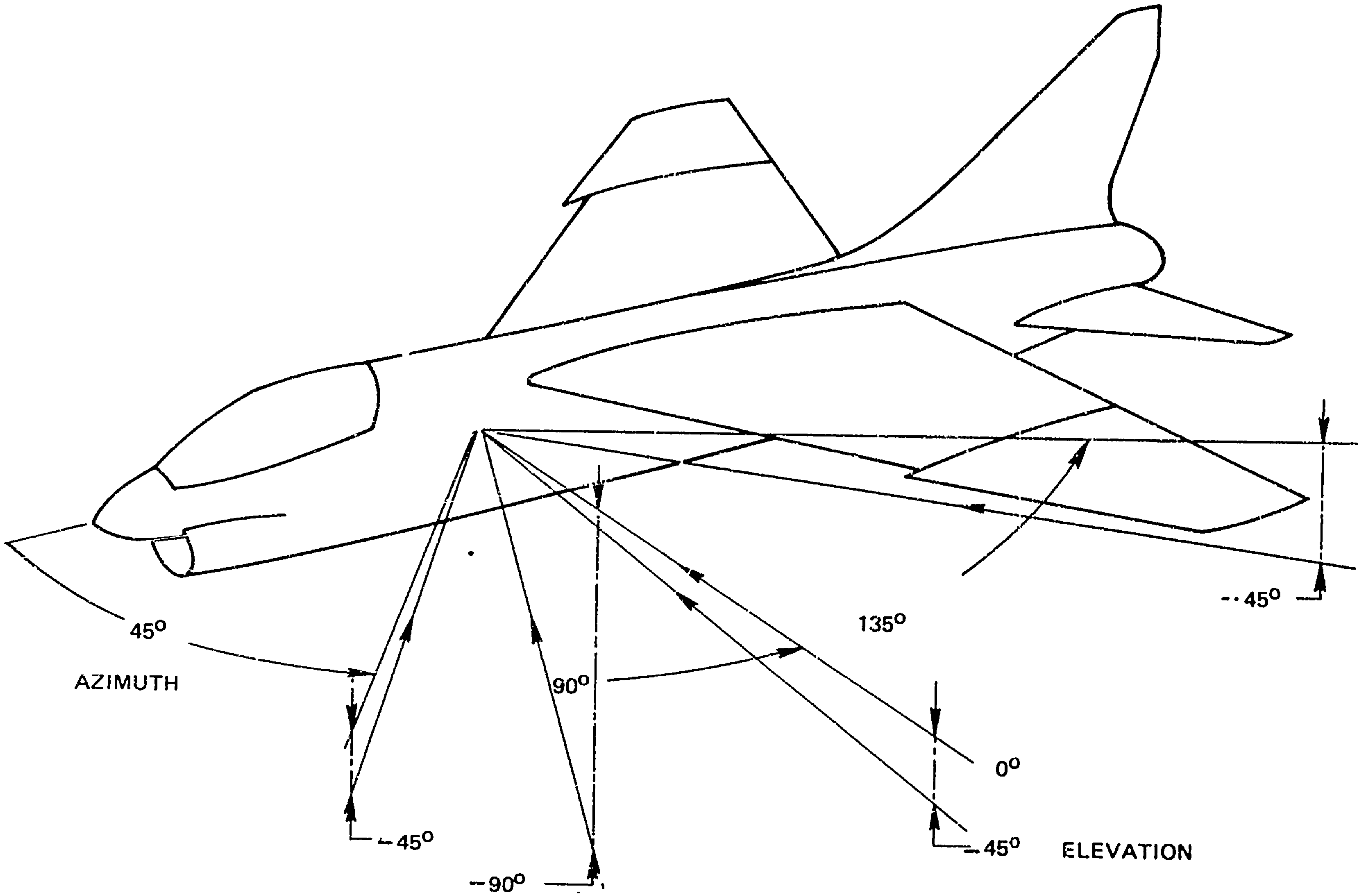

Figure 15. Threat Direction

TABLE XX SYSTEM VULNERABLE AREA SUMMARY

CONCEPT	ASPECT ANGLE IN DEGREES (AZIMUTH/ELEVATION)				
	90/0	90/0	45/-45	135/-45	90/-45
	VULNERABLE AREA IN SQUARE FEET				
1	27.18	47.48	54.25	54.75	61.72
1A	15.05	31.27	32.22	31.95	35.25
2	26.59	62.71	72.08	71.91	76.62
3	21.68	47.83	58.93	58.05	63.25
4	23.54	44.94	56.33	55.43	62.60
5	21.73	31.06	42.26	39.66	46.02
6	23.07	42.57	55.12	54.46	60.46
7	7.53	35.62	42.70	43.83	38.89
8	17.22	45.37	64.49	60.54	67.54
8A	11.74	28.13	36.63	33.01	39.70
8B	11.74	28.13	36.63	33.01	39.70
9	8.88	9.65	14.15	12.67	14.44
9A	8.88	9.65	14.15	12.67	14.44
10	27.17	34.01	46.49	39.86	52.16
11	17.94	43.61	53.32	53.68	59.66

(2) System Hits

One of the primary tasks in the survivability analysis was to determine the expected number of hits in the hydraulic system. It was assumed that the hits were uniformly and randomly distributed over the presented (or projected) area of the aircraft. Hit distribution on aircraft lost in combat operations are unknown; hence a uniform distribution appears reasonable. Another supporting consideration is the apparent degraded aiming accuracy of a .50 cal. weapon against a moving aircraft. This is true especially when the aircraft is passing through the gun envelope at high velocity and short offset distance.

Ballistic dispersion for a ring sight weapon (such as .50 cal.) is generally accepted as

$$\sigma = .3\ V$$

where σ is dispersion in mils and V is aircraft velocity in knots. Thus, for an aircraft velocity of 450 knots, the dispersion is 135 mils (one mil equals one foot at a range of 1000 feet). The single-shot probability of kill (assuming a hit is a kill) is expressed as

$$P_{K_{SS}} = \frac{A_V}{2\pi\sigma^2}$$

where A_V is the vulnerable area in square feet and σ is the dispersion in feet. Using a typical vulnerable area of 30 square feet and gun-to-target range of 1000 yards, then

$$P_{K_{SS}} = \frac{30}{2\pi\left[(135)(3)\right]^2} = .0000291$$

The probability of survival (P_S) is defined as

$$P_S = 1 - P_K$$

Therefore, for the above example

$$P_S = 1 - .0000291 = .9999709$$

Assuming a "burst" of 500 rounds,

$$P_S = 1 - (500)(.0000291) = .9854500$$

This sample analysis illustrates the shortcomings of using a survivability analysis designed for use with a total aircraft system having a relatively large vulnerable area. Few, if any, aircraft have been known to return from any one encounter with 500 hits when only the hydraulic system (or portion thereof) was considered vulnerable.

In view of the inherent limitations associated with the methodology described, an alternate method was devised to compute the

probability of survival. The assumption was made that, in each of the five aspect angles, the aircraft would receive a given number of hits uniformly distributed over the presented area of the aircraft. The hits would be of sufficient number such that the baseline (armored) hydraulic system would receive at least two hits in each of the five aspect angles considered. (Two is the minimum number of hits which will kill the baseline system if placed in the proper subsystems.) Using the assumptions stated, the number of hits on the system can be determined as follows:

$$\text{Number of hits on system} = (\text{number of hits on aircraft}) \left(\frac{(\text{vulnerable area of subsystem})}{(\text{total aircraft presented area})} \right) .$$

The vulnerable areas of the baseline system and the total presented areas of the aircraft are tabulated as follows:

Aspect Angle	Vulnerable Area System - Ft^2	Presented Area Aircraft - Ft^2
$90^\circ/0^\circ$	15.05	621.32
$90^\circ/90^\circ$	31.27	1027.53
$45^\circ/-45^\circ$	32.22	890.82
$135^\circ/-45^\circ$	31.95	896.21
$90^\circ/-45^\circ$	35.25	890.33

Based on these areas, the aircraft presented area in the $90^\circ/0^\circ$ aspect angle required more hits than the other angles in order to provide a minimum of two hits in the system vulnerable area. The required number of hits on the aircraft was determined by solving the following equation, given the number of hits in the hydraulic system.

Thus:

$$2 \text{ system hits} = (\text{"R" hits on aircraft}) \left(\frac{15.05 \text{ ft}^2}{621.32 \text{ ft}^2} \right)$$

$$\text{"R"} = 82.5 \text{ hits on aircraft (minimum)}$$

This value was rounded off to 85 hits.

All systems were analyzed using 85 hits on the presented aircraft area in each of the aspect angles considered. Thus, the aircraft presented area and number of hits uniformly distributed over this area remained constant throughout the analysis for each of the respective angles. This allowed the number of hits in the hydraulic system

to vary as the vulnerable area increased or decreased. A sensitivity analysis was conducted to determine the effects of increasing or decreasing the total hits on the aircraft. Results are presented in Appendix II.

(3) Probability of Hit

The probability of hit in each subsystem was obtained by taking the ratio of the subsystem vulnerable area to the total system vulnerable area. This method was valid because the number of hits in the system was based on the system vulnerable area (i.e., the summation of the subsystem vulnerable areas). Hits in the noncritical components or subsystems were not considered as they would not contribute to an aircraft kill by failure of the hydraulic system. A fire and/or explosion hazard could exist, but this subject was not to be considered in this study. Conditional kill probability, or the probability of kill given a hit, was assumed to be 1.0. Thus, a component or subsystem was killed if it was hit. Hits causing damage which does not result in aircraft loss were not considered.

(4) System Kill Criteria

System kill criteria was unique for each system and was dependent on the relationship between the number of subsystems and how they provided power to the critical functions. For example, in the three-hydraulic source system, Figure 3, the critical functions were divided into two groups. Both groups received power from each of the three power sources, and the loss of either group would result in an aircraft kill. In order to kill either group, all three hydraulic sources and/or respective subsystems must be killed. Therefore, the kill criteria for the three-hydraulic source system would require that all three subsystems be killed in order to effect an aircraft kill. If the system had been designed such that two subsystems jointly supplied power to one group and two different subsystems jointly supplied power to the other group, then the kill criteria could have been fulfilled in any one of three ways: (1) kill all subsystems; (2) kill the two subsystems which jointly power one group; or (3) kill the two subsystems which power the other subsystem. Thus the kill criteria for the latter (two hydraulic type) system would be different from that of the three-hydraulic system.

(5) Probability of Survival

Computation of the probability of survival was accomplished by using a binomial expansion and was subject to threat considerations previously stated. The computation model is concerned only with the projectiles which hit components within the subsystems and assumed that the hits will be uniformly distributed over the aircraft. Then for "R" hits in the system and "N" number of systems (R>N), the total system kill is averaged for each possible combination of hits. For example, let the total system be composed of system A with two subsystems and

system B with two subsystems (different from A). Assume total system survival requires that at least one subsystem in each of the systems A and B be operable. Then the probability of killing the aircraft becomes

$$P_K(\text{total system}) = P_K(\text{system A}) + P_K(\text{system B}) - P_K(\text{systems A and B})$$

where

$$P_K(\text{system A}) = f\ (P_1, P_2)$$

$$P_K(\text{system B}) = f\ (P_3, P_4)$$

$$P_K(\text{systems A and B}) = f\ (P_1, P_2, P_3, P_4)$$

Where $P_1 \ldots P_4$ are the probabilities of killing the respective subsystems[1]. The probability of total system survival is

$$P_S = 1 - P_K\ (\text{total system})$$

Derivation of a typical computational model is included in Appendix II. Several models were required because of the various kill criteria associated with the systems analyzed.

Results of the survivability analysis are shown in Table XXI. It is significant to note that the electrohydraulic power package systems (Concept No. 9 and Concept No. 9A) rated the highest of the 14 concepts analyzed. This was attributed to the relatively small vulnerable area of the system and the resulting insufficient number of hits to kill the system. The pulsating flow systems (Concept Nos. 8, 8A, and 8B) also rated high in survivability, and this was attributed to subsystem/hit relationship. Although these systems had an "average" vulnerable area when compared to the other systems, the increased number of subsystems allowed more subsystem kills which, when combined, would not result in an aircraft kill. The baseline, three-hydraulic and high pressure systems all rated relatively low because of the kill criteria and/or large vulnerable areas associated with each of the systems.

3. RELIABILITY

a. Introduction

The reliability analyses were conducted per the general requirements and methods contained in References (3) and (4). These analyses considered the operation of each system in the various performance modes (Section VI) and the definitions of subsystems (Section IV). In addition, techniques were developed for evaluating the components and

TABLE XXI PROBABILITY OF SURVIVAL SUMMARY

CONCEPT NO.	PROBABILITY OF SURVIVAL
1	.945083
1A	.978840
2	.965303
3	.978557
4	.996095
5	.994021
6	.993329
7	.993753
8	.999987
8A	.999994
8B	.999994
9	1.000000
9A	1.000000
10	.992318
11	.984114

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concepts by other than statistical methods and providing reliability inputs for the determination of the number of aircraft that should be available for a particular system and its mission requirement. In order to make the analyses as realistic as possible, the component failure rates were adjusted as necessary to reflect the improvement or degradation of the anticipated operational environments. A weighting factor of 1.5 was assigned to the failure rates of the high pressure components for the degradation effect of increasing the pressure from 3000 psi to 9000 psi. All components and systems were assumed matured for this program; however, the actual development status is significant in a reliability analysis and was considered in the component assessment. References (3) and (4) were the primary reliability data sources. No distinction was made in similar type of components for variations in physical size and flow rates (e.g., hydraulic pumps). Supporting reliability data is included in Appendix III.

b. System Ranking

An overall reliability ranking value for each system was established using the assessments: (1) component/system assessment, (2) emergency mode assessment, (3) intermediate mode assessment, and (4) the normal mode assessment. The normal mode assessment is also referred to as the system reliability. For simplicity it was assumed that all required control signals were available and that any component failure would result in functional loss of the component and its associated subsystem.

(1) Component/System Assessment

The component/system assessment provides a method of evaluating each component and system by other than statistical means. The results of the evaluation were indicative of the components and systems which can be expected to exhibit the most problem areas from fabrication through service usage. Each component was evaluated by the six parameters shown on Table XXII. Each parameter is divided into several levels with corresponding index values. The operational requirements and previous history data of each component is classified according to these levels. The numerical sum of all index values is the rating value for that component. The lower rating value (minimum value of six) represents the component which is rated best. The system assessment value is the summation of the component rating values for that system. This value is a relative ranking of the problem areas that can be expected for each system. The system assessment value for each system is shown in Figure 16. The baseline system (Concept No. 1) and the pulsating flow system (Concept No. 8) are the highest (lowest value) and the lowest (highest value) ranking systems, respectively. The assessment values for these systems are generally related directly to the total number of components in the system.

(2) Emergency Mode Assessment

The emergency mode assessment evaluates each system as to its probability of completing the mission with at least one subsystem operational for the critical functions. Subsystems which are included in a system for noncritical functions are not included in this evaluation. The results of this evaluation are shown in Figure 17. The alternate design for the electrohydraulic power package system (Concept No. 9A) ranked the highest for the probability of at least one critical subsystem being available at the end of the mission. The baseline system (Concept No. 1) ranked lowest since only two power sources were available for the flight controls and for the utilities.

The probability that any system will experience an emergency mode condition during normal airplane operations is considered extremely remote. It is recognized that the accuracy of available component data precludes accurate reliability estimates of the magnitude shown on Figure 17. However, it was necessary to carry the calculations out to a large number of places in order to show a numerical difference between the systems.

(3) Intermediate Mode Assessment

The intermediate mode assessment evaluates each system as to its probability of completing the mission with a minimum of two subsystems operational for the critical functions. Subsystems which are included in a system for noncritical functions are not included in this evaluation. The results of this evaluation are shown on Figure 18. Both the primary and alternate designs for the electrohydraulic power package system (Concepts No. 9 and 9A) ranked highest for this assessment. The baseline system (Concept No. 1) ranked lowest, since either subsystem 1 or 2 and subsystem 3 must be operational at the end of the mission for the intermediate mode condition. Comments as to the accuracy of the reliability estimates of large magnitudes, discussed in paragraph 3b(2), also apply to the intermediate mode assessment. The probability of the intermediate mode occurring is considerably greater than for the emergency mode. This is consistent with actual hydraulic system experience, since history shows hydraulic failures do occur periodically.

(4) Normal Mode Assessment (System Reliability)

The system reliability assessment evaluates each system as to its probability of successfully completing the mission with all subsystems functional within the design operational requirements. The results of this evaluation are shown in Figure 19. The electromechanical backup system (Concept No. 4) and the electrohydraulic backup system (Concept No. 6) ranked in the top two positions, respectively. This is due to the backup components being on standby until needed with all motors continuously operating. The pulsating flow system (Concept No. 8) ranked last due to the total number of components in the system.

TABLE XXII

COMPONENT RATING CRITERIA

1. Interface: Denotes possible component interface problem areas with other components, systems, or operating environmental conditions.

   1 - No known or significant interface problems

   2 - Minor interface problems

   3 - Major interface problems requiring special provisions and/or procedures

   4 - Major interface problems requiring isolation provisions

2. Qualification/Usage Status: Denotes degree of component data, or service history available.

   1 - Qualified and/or extensive service usage

   2 - Qualified only and/or some service usage

   3 - Unqualified and/or relatively new component

3. State-of-the-Art: Denotes the degree of component development.

   1 - Proven design

   2 - Design verification tests in process or complete

   3 - Conceptual testing in process

   4 - Conceptual feasibility design stage

   5 - Conceptual definition stage

4. Complexity: Denotes the design complexity.

   1 to 10 - General rating of total number of parts and/or design complexity which will have direct bearing on manufacturing, checkout, or testing requirements, installation, and maintenance, thereby influencing the overall reliability of the component.

TABLE XXII (Cont'd)

COMPONENT RATING CRITERIA

5. <u>Manufacturing</u>: Denotes degree of problems that will be the result of manufacturing processes and procedures and undetected discrepancies.

   1 - Simple manufacturing techniques with no special or elaborate processes and procedures

   2 - Average manufacturing processes and procedures

   3 - Close tolerances and some special processes and/or procedures

   4 - Complex part/assembly requiring close tolerances and estra special procedures

6. Predicted Reliability

   Value = Failure rate per million hours times 10^4

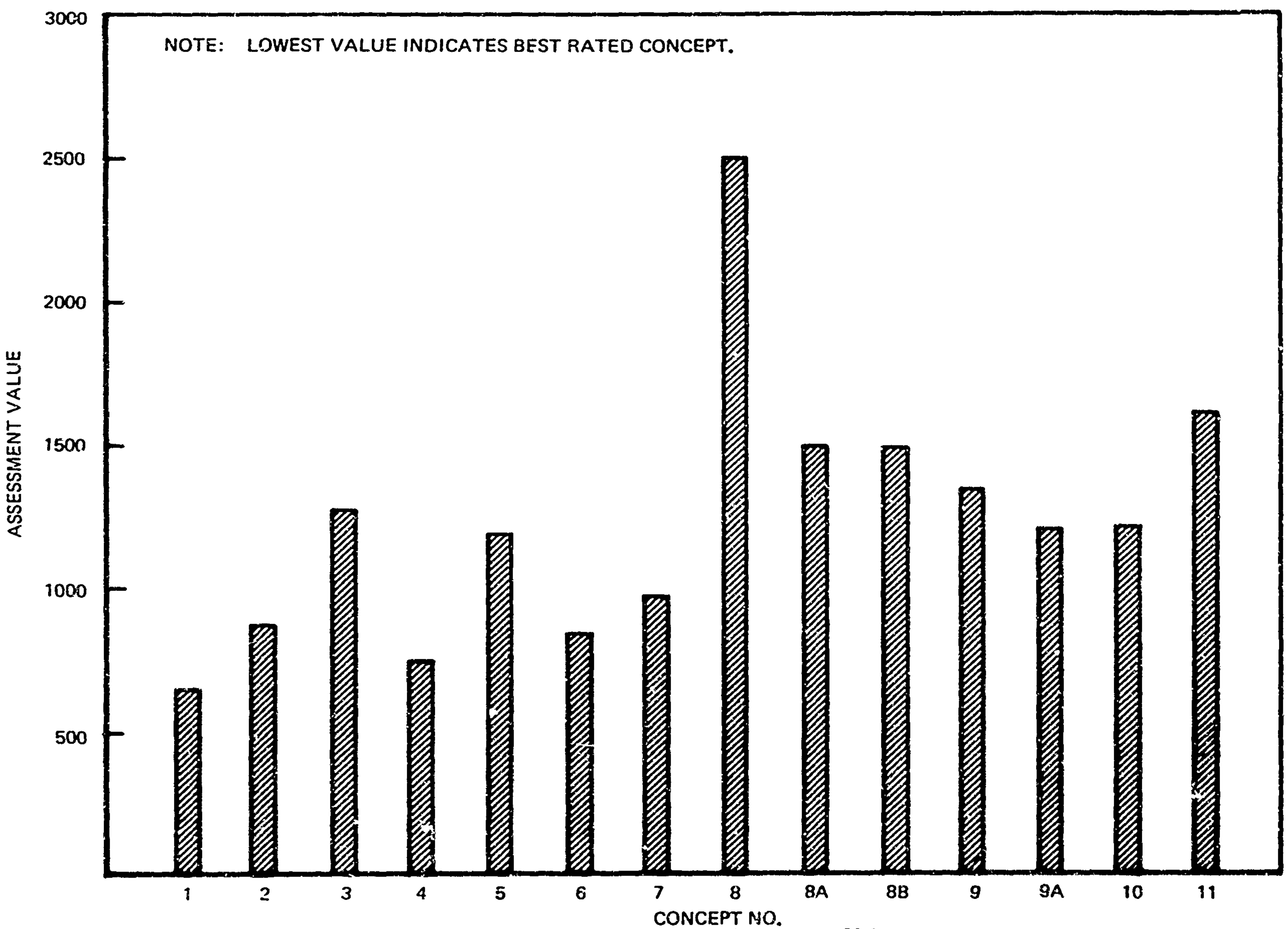

Figure 16. System Assessment Value

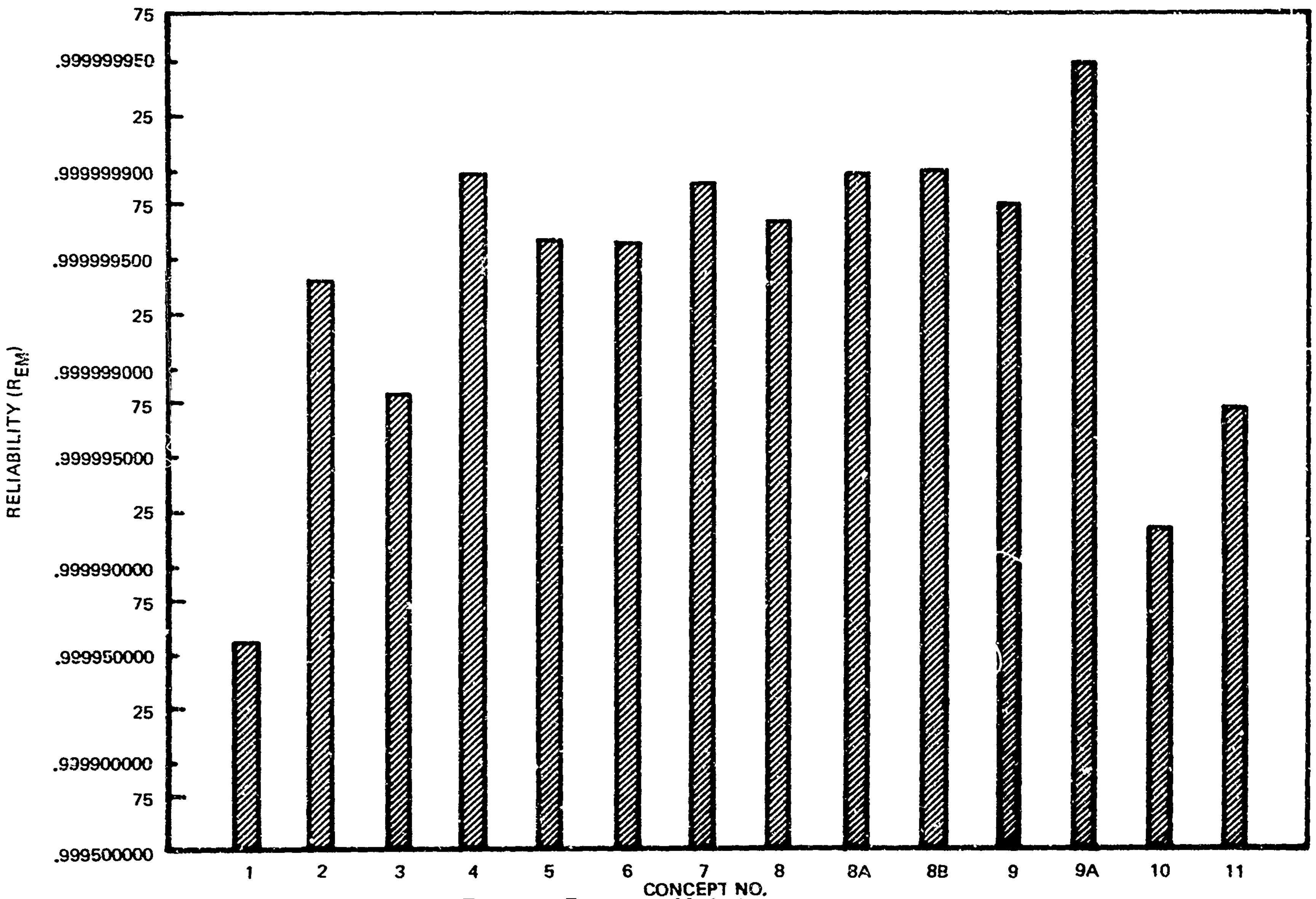

Figure 17. Emergency Mode Assessment

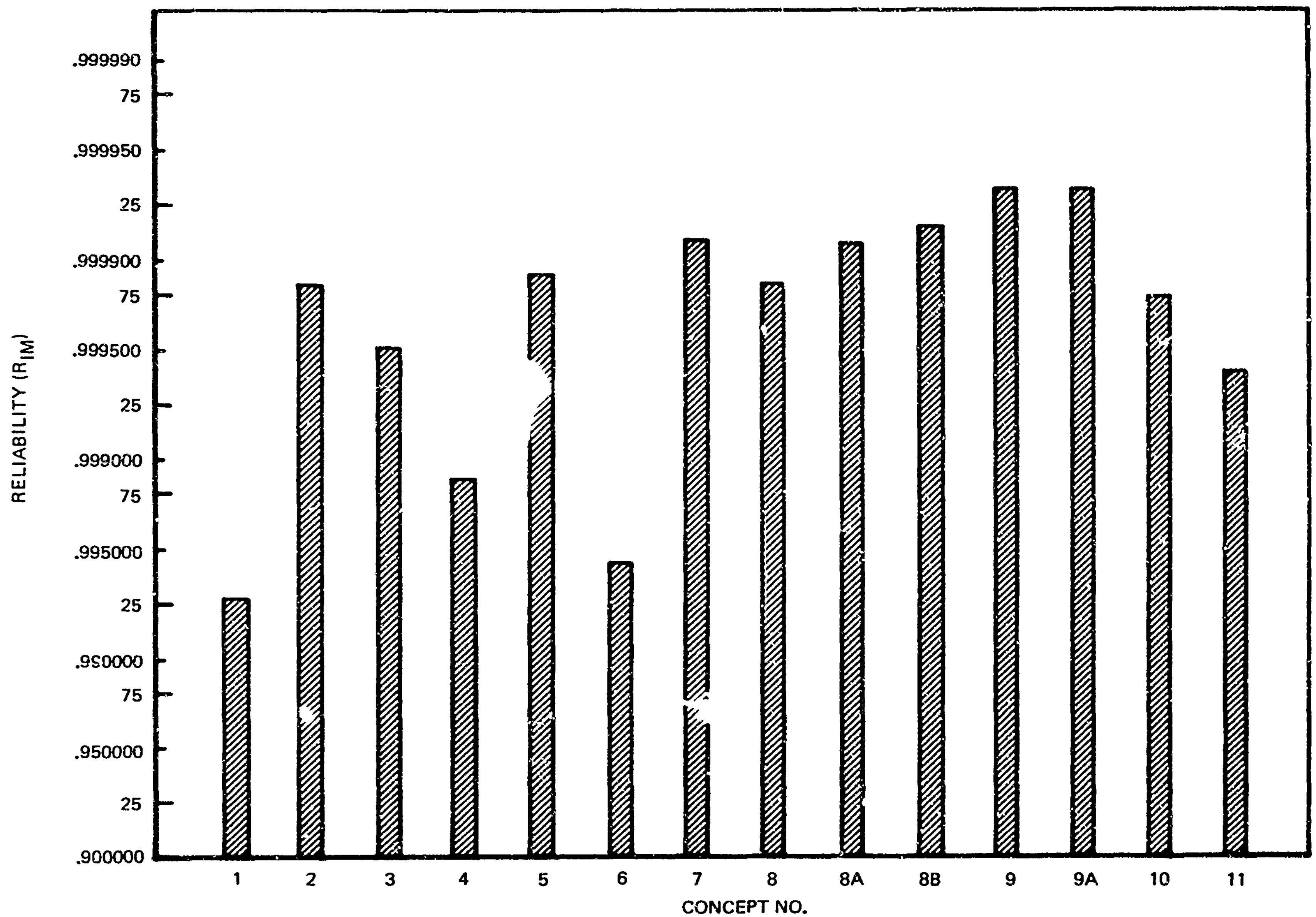

Figure 18. Intermediate Mode Assessment

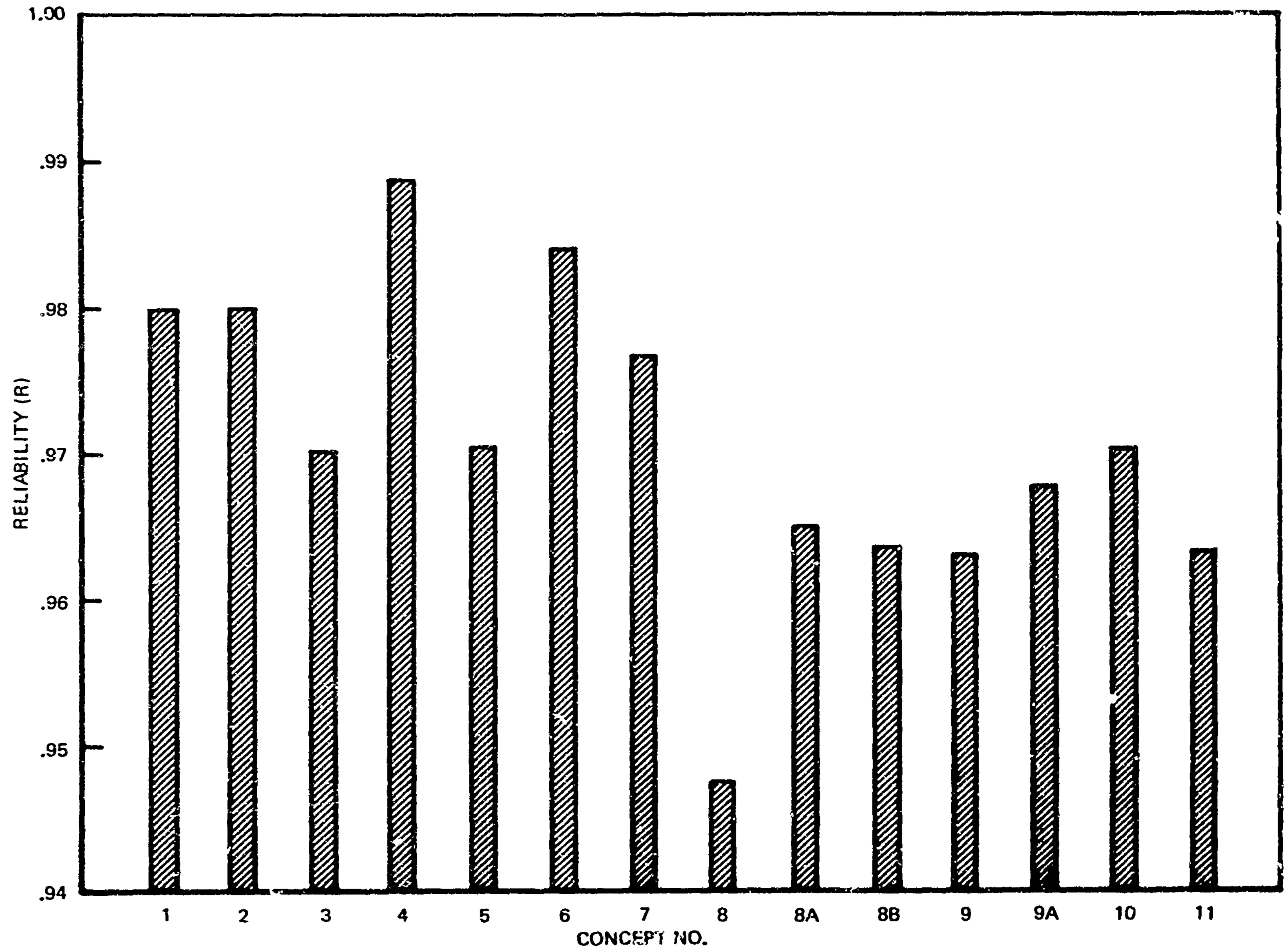

Figure 19. System Reliability (Normal Operational Mode)

(5) Reliability Ranking Value

Results of the four assessments were normalized and combined into an overall numerical ranking value using weighting factors. In establishing the weighting factors for each of the four evaluation parameters, the importance of having at least one critical subsystem operational at the end of the mission and a minimum amount of system degradation was recognized. However, the primary objective of any reliability program is to ensure that there is no system degradation during a mission. Therefore, results of the component/system assessment and the normal mode assessment were considered the two most important parameters. Several trials were made using different weighting factors for each of the values in Figures 16, 17, 18, and 19. Additional trials were made using the effective failure rate and the effective mean-time-between-failures (MTBF) in place of the reliability values in Figures 17, 18, and 19. The effective failure rate or MTBF is the resultant value associated with the system predicted reliability value and includes the benefits of components being operationally redundant or in a standby condition during a normal mission. There was basically no shifting in the ranking position of the top six systems in all of the trials. The combination of parameters selected for determining reliability ranking value consists of the system assessment value and the effective failure rate in place of the reliability value for each operational assessment. Weighting factors selected for each assessment are shown in Table XXIII. The reliability ranking values are shown in Figure 20.

TABLE XXIII

SYSTEM RANKING VALUE WEIGHTING FACTORS

Assessment	Weighting Factor
Assessment Value	.15
Emergency Mode Assessment	.20
Intermediate Mode Assessment	.15
Normal Mode Assessment (System Reliability)	.40

c. Operational Cost Inputs

Reliability inputs to operational cost estimates consisted of the mean-time-between-failures and the operational reliability values for each system.

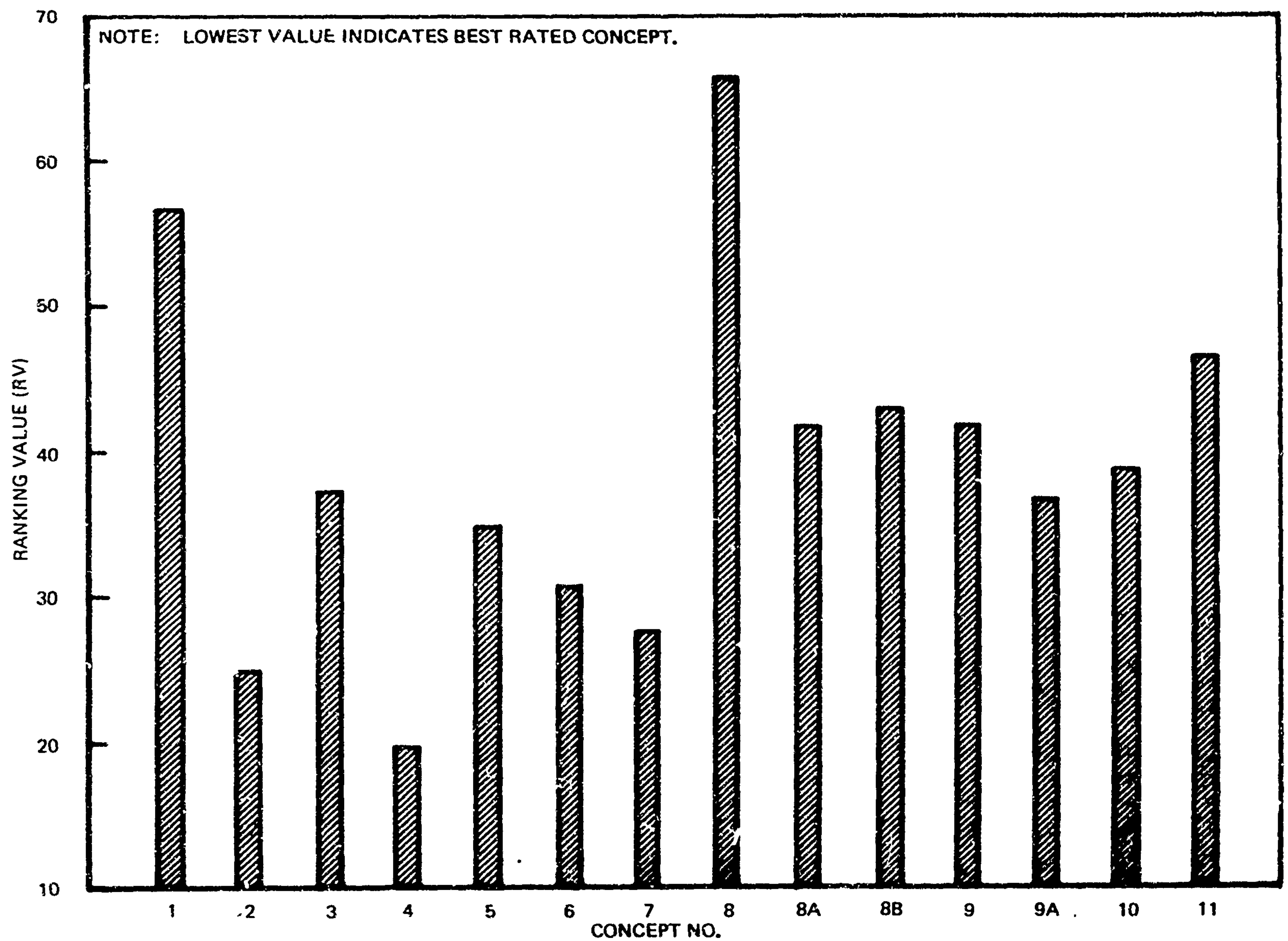

Figure 20. Reliability Concept Ranking

(1) System Mean-Time-Between-Failures

The system mean-time-between-failures (MTBF) is defined as the mean time that failure can be expected and that replacement of components will be required. This parameter was utilized in the establishment of the amount and costs of the spares that would be required to support each system. However, the determination of the components which require scheduled maintenance repair or replacement action and the frequency of occurrence were not included in this study. Figure 21 shows the MTBF value for each system. The electromechanical backup system (Concept No. 4) and the baseline system (Concept No. 1) have the highest MTBF values, while the pulsating flow system (Concept No. 8) has the lowest value. The higher MTBF for the electromechanical backup system is primarily attributed to the use of electrical screwjacks as backup actuators with only the electrical motors operating during the entire flight. The MTBF values for the baseline system and the pulsating flow system are primarily attributed to the total number of components in each system. Among all the systems, these two systems contain, respectively, the least and greatest number of components.

(2) Operational Reliability

Operational reliability is defined as the probability of an airplane taking off and completing its mission within operational requirements after the airplane has been declared ready for flight. This parameter is used in determining the number of aircraft that must be available for the mission. The probability that an air abort will not occur and the mission (delivery of payload and return) will be completed was assumed approximately equal to the system reliability value determined from the normal mode assessment. The operational reliability is expressed as follows:

$$R_O = (1 - KP_A)\,R$$

where R_O = operational reliability

K = system complexity

P_A = ground abort rate

R = system reliability

(a) System Complexity (K)

Each component (hydraulic, mechanical, or electrical) was assumed to have an equal effect on both the complexity and the performance of each system. The system complexity value is then directly proportional to the total number of components in the system being evaluated. Values were determined for each system with reference to the baseline system which has a value of unity and contains 67 components. The complexity value is expressed as:

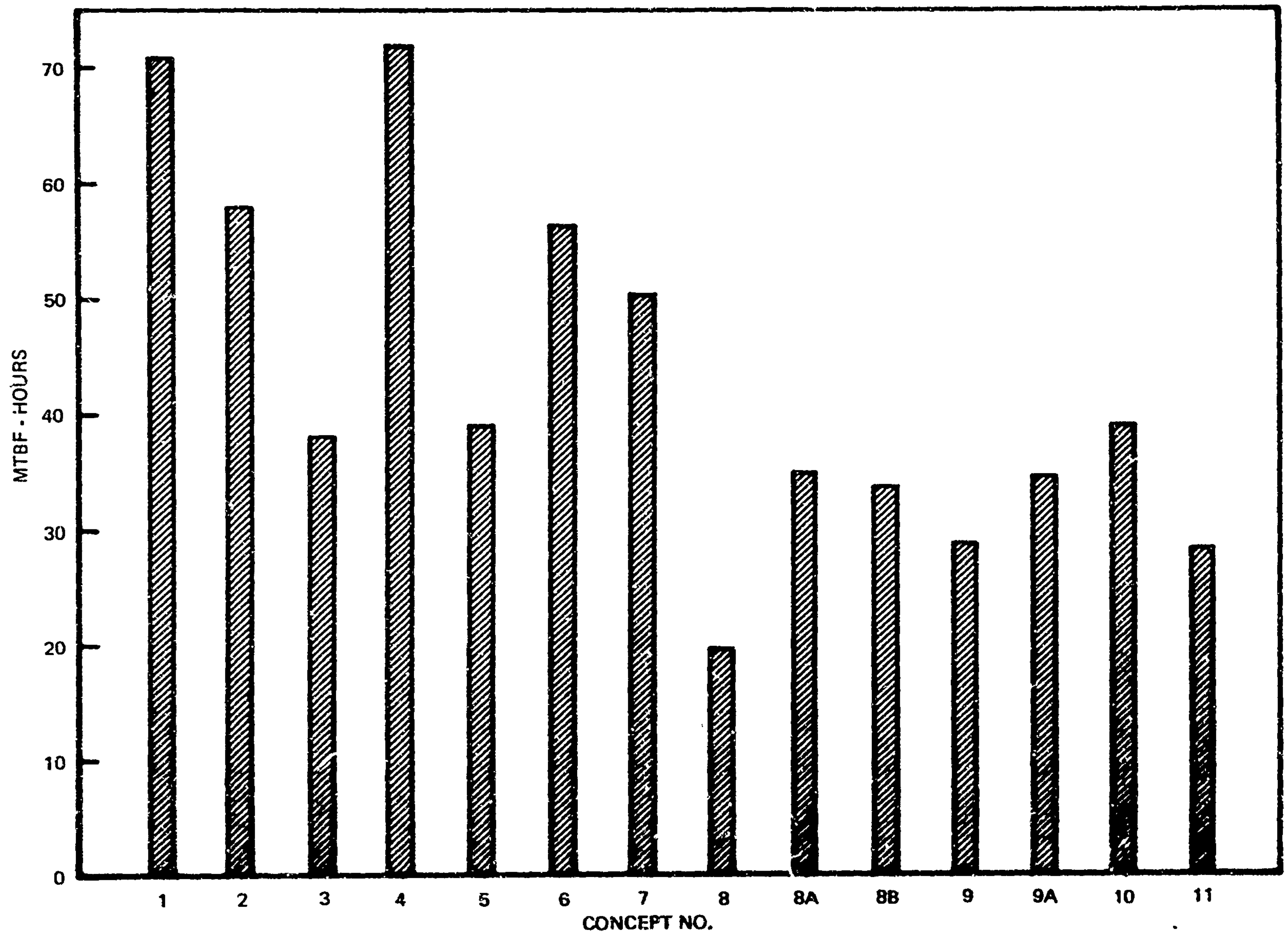

Figure 21. System Mean-Time-Between-Failure

$$K = \frac{n}{N}$$

where K = complexity value

n = total number of system components

N = number of components in baseline system

(b) Ground Abort Rate (P_A)

The ground abort rate is defined as the probability that a ground abort will occur which is attributed to failure(s) of the hydraulic system. The rate used was 1.353 percent of attempted flights derived from data in Reference 5. These data are from world-wide activities, and only the ground aborts that could be attributed to confirmed failures of the hydraulic system were used in establishing the ground abort rate.

(c) System Reliability (R)

This parameter is defined in paragraph 3b(4) of this section.

(d) Operational Reliability Values

Results of this evaluation are shown in Figure 22 with system reliability values replotted from Figure 19. A comparison of the operational and system reliability values indicates no significant effect on system ranking position, when the complexity value and the ground abort rate are considered.

(e) Data Summary

A summary of the reliability evaluation parameters used in the overall system rating and cost evaluations is shown by Figure 23. These parameters are system ranking value, system mean-time-between failures, and operational reliability. The plot for the system ranking value is reversed in order that its pattern may be compared directly with the other two parameters. The electromechanical backup system (Concept No. 4) and the pulsating flow system (Concept No. 8) ranked highest and lowest, respectively, for each of the three evaluation parameters.

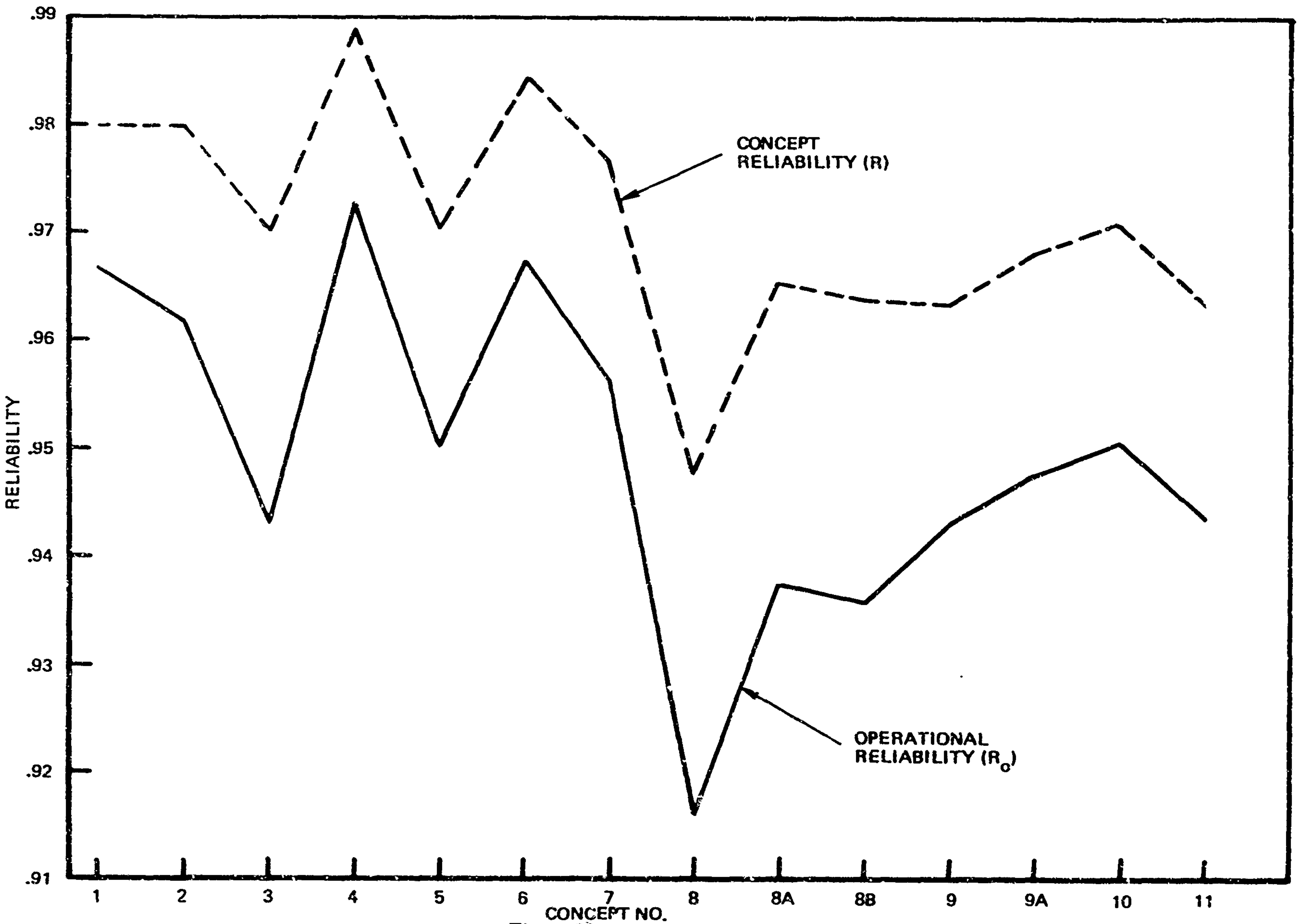

Figure 22. Operational Reliability (R_o)

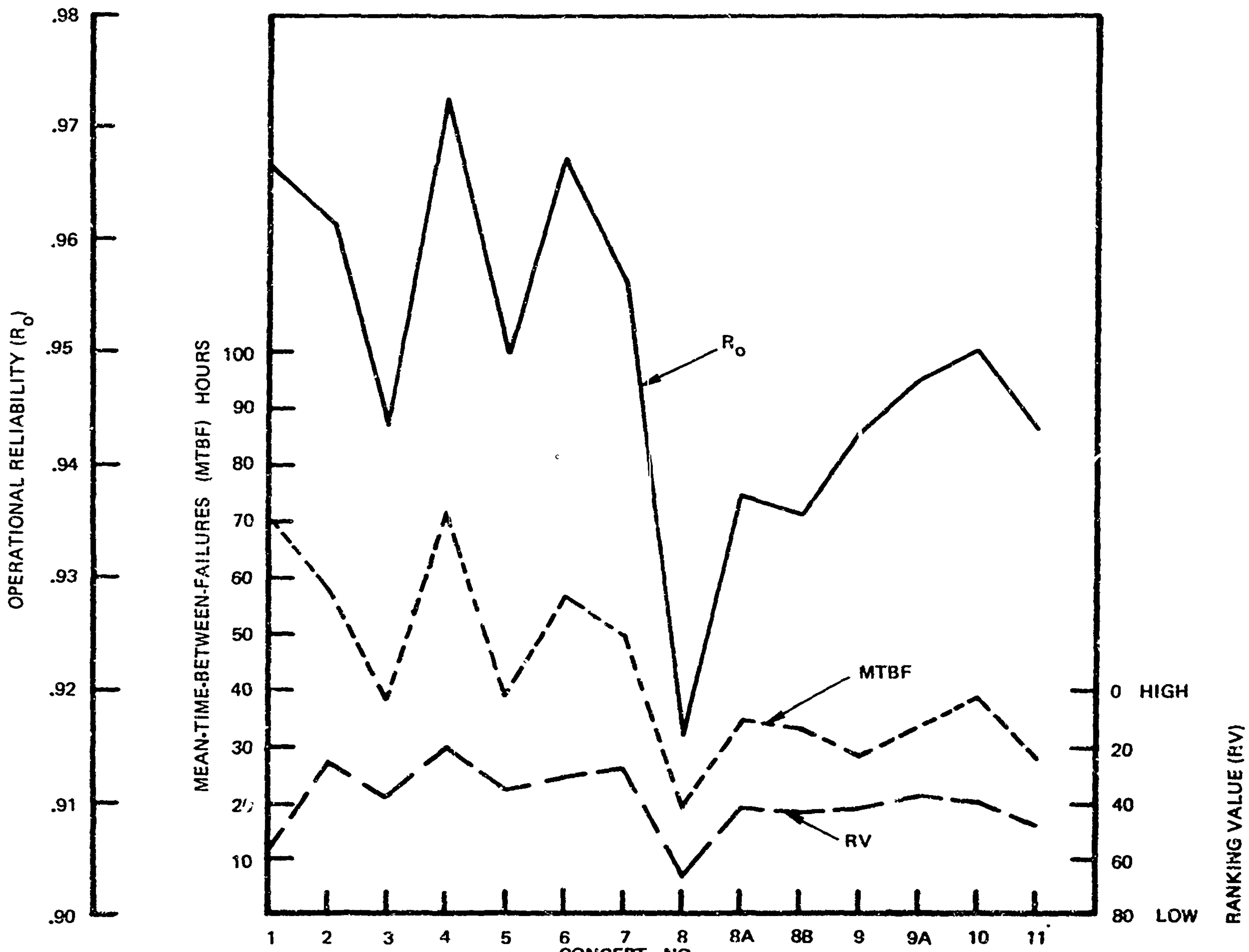

Figure 23. Reliability Evaluation Summary

4. MAINTAINABILITY

a. Introduction

Each system was evaluated for impact on maintainability. The evaluation resulted in maintenance indexes and maintenance costing data. Maintenance data on the component level were derived from similar data on existing aircraft.

b. Maintenance Index

(1) Methods

The number of systems and level of system definition indicated that a qualitative evaluation would be necessary to determine the relative maintainability for each system. A maintenance index was devised from a review of maintenance characteristics which reflect maintainability. Six parameters, considered the most significant indicators of a hydraulic component's inherent maintainability, were selected from these characteristics. These parameters are shown in Table XXIV along with scales reflecting varying degrees of maintainability degradation. These indexed parameters were used to evaluate the maintainability of each component in each system. The same component may have different indexes due to its location in the system and airplane.

(2) Results

A summary of typical components and their resulting index values is presented in Table XXV. Components for each system are defined in Appendix I. The component indexes were summed to obtain system maintenance indexes shown in Table XXVI. The lower the concept index, the more maintainable a system was considered to be. Each system was compared to the baseline in terms of increase in maintenance. The baseline system ranked the highest with the minimum maintenance index. This system represents conventional aircraft hydraulic systems and contains the minimum number of components. The maintenance impact of armor-plating the system was not evaluated. The backup systems ranked high due to the use of electrohydraulic actuators (Concept No. 4) and the use of electric driven motorpump packages (Concept No. 6) in place of one hydraulic pump package (pump, reservoir, accumulators, and filters). The pulsating flow system (Concept No. 8) ranked lowest since the number and type of components made the servicing and inspection requirements unsatisfactory. Modifications to this system (Concept Nos. 8A and 8B) reduced the maintenance index appreciably through the reduction of components, primarily those requiring servicing and inspection (i.e., transformers).

TABLE XXIV MAINTENANCE INDEX NUMERICAL SCALES

1. Complexity Index: Number of parts (except attaching hardware)

2. Operability Index

0 - No moving parts

1 - No moving parts with temperature or pressure above or below ambient

Move at low rotational or linear speeds by:

4 - Mechanical power

5 - Noncombustible fluid power

6 - Noncombustible gas power

7 - Electric power

8 - Combustible fluid power

9 - Combustible gas power

Move at high rotational or linear speeds by:

12 - Mechanical power

13 - Noncombustible fluid power

14 - Noncombustible gas power

15 - Electrical power

16 - Combustible fluid power

17 - Combustible gas power

20 - Tubes, transistors, diodes

TABLE XXIV MAINTENANCE INDEX NUMERICAL SCALES (Continued)

3. Access Index

A. Access Provisions

0 - Direct access

5 - Quick-opening door - no tools

10 - Quick-opening door - tool required

15 - Stressed door or panel

B. Height above Ground

0 - 0-5 feet

5 - 6-15 feet

10 - Over 15 feet

C. Miscellaneous Access

5 - If one or more components must be removed to gain access

10 - If sealant is required as result of access

4. AGE and Tool Index

0 - No tools or AGE required

2 - Required common hand tools

4 - Requires standard AGE

6 - Requires special tools and/or AGE

5. Scheduled Maintenance Index

0 - No scheduled maintenance

2 - IRAN

4 - Periodic or forced replacement time

6 - Post-flight or routine servicing

8 - Preflight inspection

TABLE XXIV MAINTENANCE INDEX NUMERICAL SCALES (Continued)

6. Miscellaneous Index

5 - Special skills required

10 - Potential safety hazard

Component Maintainability Index equals the sum of the individual indexes.

Concept Maintainability Index will equal the sum of all the component indexes.

TABLE XXV TYPICAL COMPONENT MAINTAINABILITY SUMMARY

Component	No. of Maint. Actions (per 1000 FH)	MMH/FH	Maintenance Index
Accumulator	.50	.004	26
Accumulator, Emergency	.83	.005	42
Actuator, A. G.	2.00	.012	95
Actuator, Aileron	2.00	.023	110
Actuator, Aileron, Mechanical	1.00	.007	75
Actuator, Flap	1.00	.007	65
Actuator, Flap, Mechanical	.20	.001	65
Actuator, L. G. Door, Mechanical	.20	.001	45
Actuator, M. G.	.50	.003	66
Actuator, M. G. Door	.33	.002	66
Actuator, N. G.	.50	.003	37
Actuator, N. G. Door	.33	.002	34
Actuator, N. G. Steering	2.00	.007	79
Actuator, Refuel	1.00	.005	58
Actuator, Rudder	.75	.006	65
Actuator, Speed Brake	.50	.004	59
Actuator, Spoiler	.60	.005	63
Actuator, UHT	.50	.005	150
Actuator, UHT, Mechanical	1.00	.008	75
Brake Valve	.50	.002	28
Filter	.10	.000	26
Generator Package	6.82	.035	285
Generator Package, Dual Drive	8.70	.052	335
Motor Pump, Electric	2.00	.017	140
Motor Pump, Hydraulic	2.50	.023	143
Motor Pump, Pneumatic	2.40	.020	114
Pump, Engine Driven	1.25	.011	90
Rectifier, 1-Phase	.51	.002	55
Rectifier, 2-Phase	.78	.003	70
Rectifier, 3-Phase	1.08	.004	85
Reservoir	.33	.003	36
Selector Valve, AG	.20	.001	54
Selector Valve, Emergency	.20	.000	42
Selector Valve, Flap	.15	.000	41
Selector Valve, L. G. and Door	.15	.000	30
Selector Valve Package	2.11	.010	95
Selector Valve, Speed Brake	.25	.001	44
Selector Valve, Refuel	.20	.000	59

TABLE XXV TYPICAL COMPONENT MAINTAINABILITY SUMMARY (Continued)

Component	No. of Maint. Actions (per 1000 FH)	MMH/FH	Maintenance Index
Shutoff Valve, Emergency	.20	.000	22
Shutoff Valve Package	1.99	.014	85
Transformer	.60	.002	42
Valve Package, Alternator	2.40	.022	82
Volume Compensator	.40	.006	44

TABLE XXVI MAINTAINABILITY RANKING SUMMARY

RANKING	CONCEPT NO.	CONCEPT TITLE	MAINTENANCE INDEX	% INCREASE
1	1	Baseline	4.034	0
2	4	Electromechanical Backup	5.033	24.8
3	6	Electrohydraulic Backup	5.686	41.0
4	2	Three Hydraulic Sources	5.715	41.7
5	3	High Pressure System	5.883	45.8
6	7	Five Hydraulic Sources	6.127	51.9
7	5	Flywheel Power	7.080	75.6
8	11	Automatic Failure Isolation	7.088	75.7
9	10	Motorpump Isolation	7.175	78.0
10	9A	Electrohydraulic Power (Modified)	7.587	88.1
11	9	Electrohydraulic Power	8.349	107.0
12	8B	Pulsating Flow (Modified)	8.693	115.5
13	8A	Pulsating Flow (Modified)	8.737	116.8
14	8	Pulsating Flow	13.174	226.5

c. Maintenance Costing Data

Maintenance data for the cost evaluation consisted of estimates for maintenance actions per 1000 flight hours and maintenance manhours per flight hour (MMH/FH). These estimates were derived with manpower estimates based on existing components and scheduled maintenance with no interface requirements included (i.e., rigging and synchronization). All systems were assumed matured. For this study, a maintenance action was defined as an action required to preclude the occurrence of a malfunction (preventive maintenance) or restore an equipment to a satisfactory operating condition (corrective maintenance). Preventive maintenance was determined at the system level. Corrective maintenance was determined for each component and then summed to obtain the system value. Table XXV presents a summary of typical components and values used in this study. A summary of the resulting maintenance costing data is contained in Table XXVII.

5. WEIGHT

a. Methods

Each system was evaluated using conventional weight estimating methods, tempered by experience factors gained from current production aircraft. Weight estimating was based primarily on similarity to existing components. In addition to the components and tubing, weight estimates were made for system fluid and additional miscellaneous components not included in the system definition but required to complete an aircraft system. These latter components include tube fittings, check valves, relief valves, filler valves, etc., that, by definition, were not essential in performing the system functions. System weights were used for both value rating and costing efforts.

b. Results

Total system weights are shown in Table XXVIII with general breakdowns. Table XXIX provides weight ranges for the types of components in each system. The baseline system is the lightest system, since it has fewer components and is simplest in design. Armorplate was added to protect vulnerable areas, causing the weight to increase by a factor of two. Thus the baseline system became the heaviest system. The amount of armorplate was determined from area projections, instead of installation design, to simplify the vulnerability evaluation. These areas are defined in the definition of the baseline system in Section VI. From a weight viewpoint, approximately 50% of the basic system weight would be reasonable for armorplate. When system redundancy was increased in defining the remaining systems, an additional set of actuators was added. The electrohydraulic backup system (Concept No. 6) is the second lightest system. The weight increase for Concept No. 6 was low, since the backup actuators were smaller than the norm

TABLE XXVII MAINTENANCE COSTING DATA SUMMARY

CONCEPT NO.	CONCEPT TITLE	MAINTENANCE ACTIONS PER 1000 FH	MMH/FH
1	Baseline	466.32	.480
2	Three Hydraulic Sources	490.24	.655
3	High Pressure System	522.73	.861
4	Electromechanical Backup	473.52	.463
5	Flywheel Power	571.09	.869
6	Electrohydraulic Backup	486.78	.593
7	Five Hydraulic Sources	496.12	.761
8	Pulsating Flow	628.18	1.937
8A	Pulsating Flow (Modified)	546.25	1.036
8B	Pulsating Flow (Modified	544.71	1.102
9	Electrohydraulic Power	537.76	1.308
9A	Electrohydraulic Power (Modified)	526.27	1.089
10	Motorpump Isolation	517.59	.871
11	Automatic Failure Isolation	524.58	.874

TABLE XXVIII SUMMARY OF SYSTEM WEIGHTS

CONCEPT	COMPONENTS	TUBING AND WIRING	FLUID IN TUBES	FITTINGS AND MISC. VALVES	TOTAL WEIGHT
1	730	141	73	300	1,244
1A	*2,230	141	73	300	2,744
2	951	151	76	308	1,486
3	1,196	163	29	344	1,732
4	1,234	153	65	260	1,712
5	1,175	185	87	392	1,839
6	859	131	69	278	1,337
7	996	150	76	318	1,540
8	1,264	241	93	509	2,107
8A	1,051	285	112	587	2,035
8B	1,081	285	112	587	2,065
9	1,440	372	40	562	2,414
9A	1,360	350	51	542	2,303
10	1,126	185	87	392	1,790
11	956	151	75	320	1,502

*Includes 1,500 pounds of armorplate

TABLE XXIX COMPONENT WEIGHTS

Component	Weight (Pounds)
Accumulator	3 - 12
Actuator	
Aileron (Hydraulic)	12 - 35
Aileron (Electromechanical)	15 - 41
Air Refuel	9 - 16
Arresting Gear	14 - 21
Flap	6 - 14
Main Gear	23 - 35
Main Gear Door	4 - 12
Nose Gear	9 - 13
Nose Gear Door	4 - 12
Nose Gear Steering	20 - 32
Rudder	10 - 18
Speed Brake	24 - 44
Spoiler	8 - 17
UHT	14 - 44
Alternator, Hydraulic	8 - 10
AFI Package	3 - 6
Brake Valve	2
Filter	4 - 8
Flywheel Package	34 - 56
Motorpump, Electric	43 - 62
Motorpump, Hydraulic	38 - 59
Pump	12 - 35
Rectifier, Hydraulic	1 - 4
Reservoir	10 - 44
Selector Valve, Electric	1 - 4
Selector Valve, Manual	1 - 2
Transformer, Hydraulic	1 - 12

TABLE XXX COMPONENT EFFICIENCIES

Component	Efficiency (%)
Pump	90
Generator	80
Electric Motorpump Package	76
Hydraulic Motorpump Package	80
Flywheel Power Package	43
Hydraulic Alternator	90
Hydraulic Transformer	90
Hydraulic Actuator	90
Hydraulic Actuator (Concept No. 3 only)	70
Electromechanical Actuator	48

operating actuators, and the aircraft electrical power source (not defined as part of the system) was used in place of a hydraulic power source. The electrohydraulic power package system (Concept No. 9) has the highest weight (next to the armor-plated baseline) since it contains electrical generators and numerous electrically driven motorpumps. In general, the weights of each system containing only hydraulic components were related to the total number of components. The baseline system without armor contains 67 components and weighs 1,244 pounds, while the pulsating flow system (Concept No. 8) contains the greatest number of components, 166, and weighs 2,107 pounds.

6. PERFORMANCE

a. Introduction

Each system was evaluated for certain performance parameters in all three modes of operation. The overall system efficiency was determined for the normal mode and expressed in terms of power drain on the engines. The effect of losing one engine was examined for the intermediate mode, and the effect of losing any two power sources was examined for the emergency mode. The degree of isolation was evaluated as a function of the relationship of critical and noncritical actuators (functions) in the same subsystem. These four evaluation parameters are expressed as penalty ratings on the system; thus, the smallest rating indicates the best system. These four evaluations were weighted and combined into a performance rating value for each system. These values were adjusted to relate the highest value with the best system. An example of performance evaluation is given in Appendix IV.

b. Evaluation Methods and Results

(1) System Efficiency

All systems are designed for the same output requirements. Input requirements (power from engines) will vary because of inherent system efficiencies. For this evaluation system efficiency considered only the efficiencies of power generation or conversion components and actuators. Further, the evaluation considered only the operating conditions described in paragraph 1b of Section VI. This condition is the peak power demand based on a combination of flight control functions. Knowing the output requirements, the input requirements (power) were determined using the component efficiencies listed in Table XXX. Actuator efficiencies account for line losses in a gross manner. An additional 90% was allowed for the effects of pulsating flow. Input power requirements (engine power drain) are shown in Figure 24; the required output power shown is 233 HP for all systems. These input power requirements are used as cost factors in determining the total system costs. Concept No. 3 requires the highest input due to the effects of high pressure (9,000 psi) on system efficiency. Concept No. 9 has a high input requirement due to the extensive use of less efficient

components; i.e., generators and motorpumps. Concept No. 1 has a low power drain due to the use of fewer actuators than in the other concepts. Concept No. 5 requires the least power input due to the use of flywheel energy at the speed brake. Input pneumatic power at the flywheel is only about 10% of the power required in systems using engine-driven power sources for speed brake operation.

(2) Loss of One Engine

The loss of one engine will affect the engine-driven power source and the associated functions. The effects will vary depending on the arrangement of functions and power sources. System losses were expressed in terms of power lost to the functioning element resulting from loss in actuation capability. For example, in Concept No. 2, three independent actuators (three subsystems) power one aileron. Loss of one engine loses one subsystem and one actuator, resulting in a loss of one-third power to one aileron. Each system was analyzed in this manner for either engine lost. The losses were summed with weighting factors applied for the different types of actuators based on usage: critical flight controls and utilities, noncritical flight controls, flaps, and noncritical utilities. These sums are expressed as ratings in percent of the maximum penalty. Resulting ratings were averaged for both engines and are shown in Figure 25. The two backup systems (Concept No. 4 and Concept No. 6) carried the heaviest penalty, since only two subsystems are operating during normal conditions. The baseline system has the lowest penalty due to the simple system arrangement.

(3) Loss of Two Power Sources

The loss of two power sources will result in the loss of two subsystems, which may place the system in the emergency mode. The number of subsystems varied among the systems as well as the relationship of functions and subsystems. This evaluation was conducted in a manner similar to that in the preceding paragraph. In each system, all possible combinations of two power sources were examined for loss effects. Losses were summed with weighting factors applied and then averaged to obtain the penalty rating value in percent of the maximum penalty. These results are shown in Figure 26. Concept Nos. 5 and 7 show the lowest penalties due to the maximum separation of critical and noncritical functions achieved by the use of five power sources. The two power sources in Concept Nos. 8 and 8A can be lost as the result of hits on the power supply transformers. Loss of these components also causes loss of two common pulsating flow lines. This leaves one line with one-third flow capability and one actuator (i.e., aileron) operating on one phase, producing one-third load capability. This reduction in capability results in Concept Nos. 8 and 8A having the highest penalties.

(4) Function Isolation

This evaluation was conducted to panelize systems with subsystems powering both critical and noncritical functions or actuators. The rating value is the ratio of noncritical functions (actuators) to the total number of functions (actuators) in the system. This

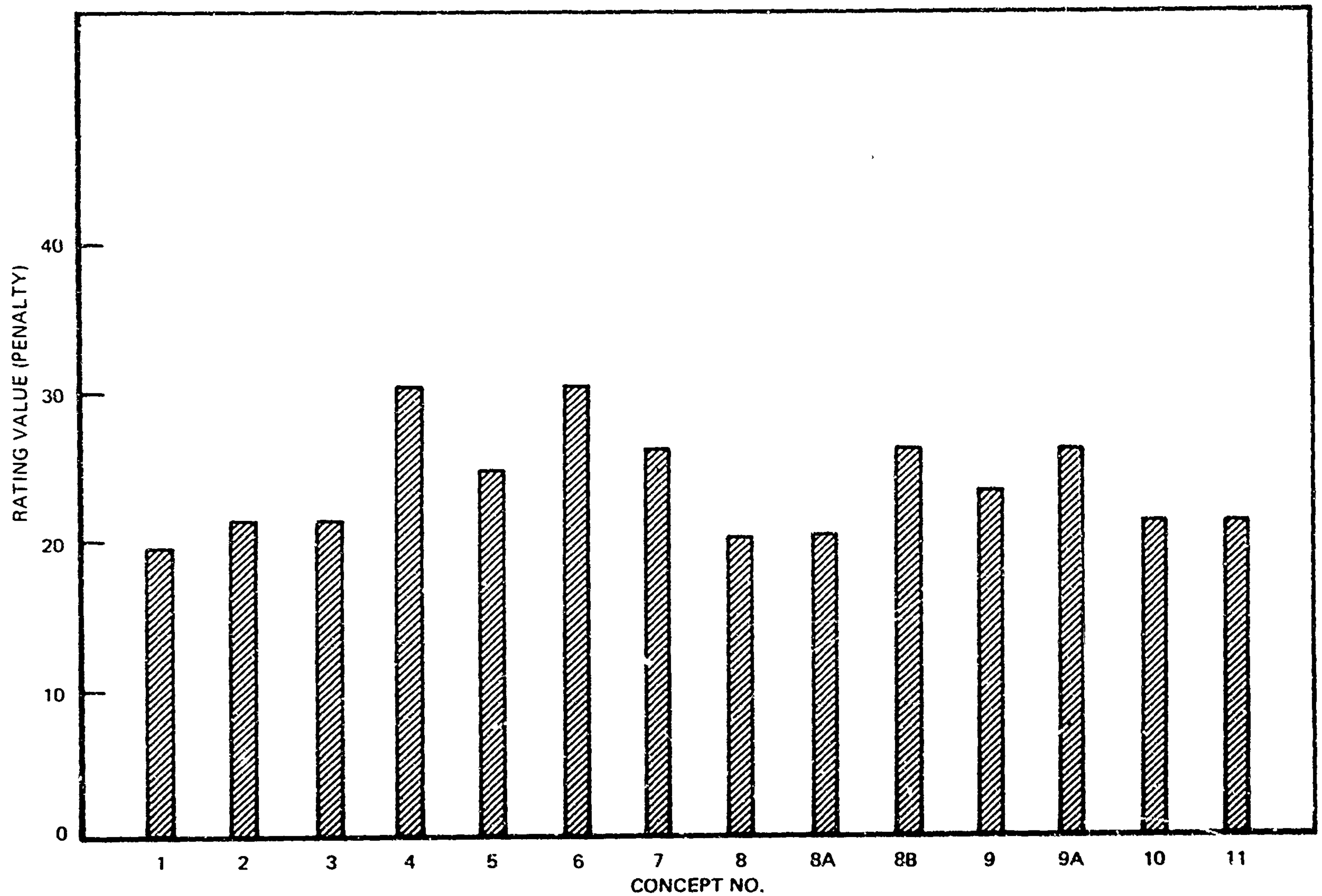

Figure 25. Effect of Engine Loss on System Performance

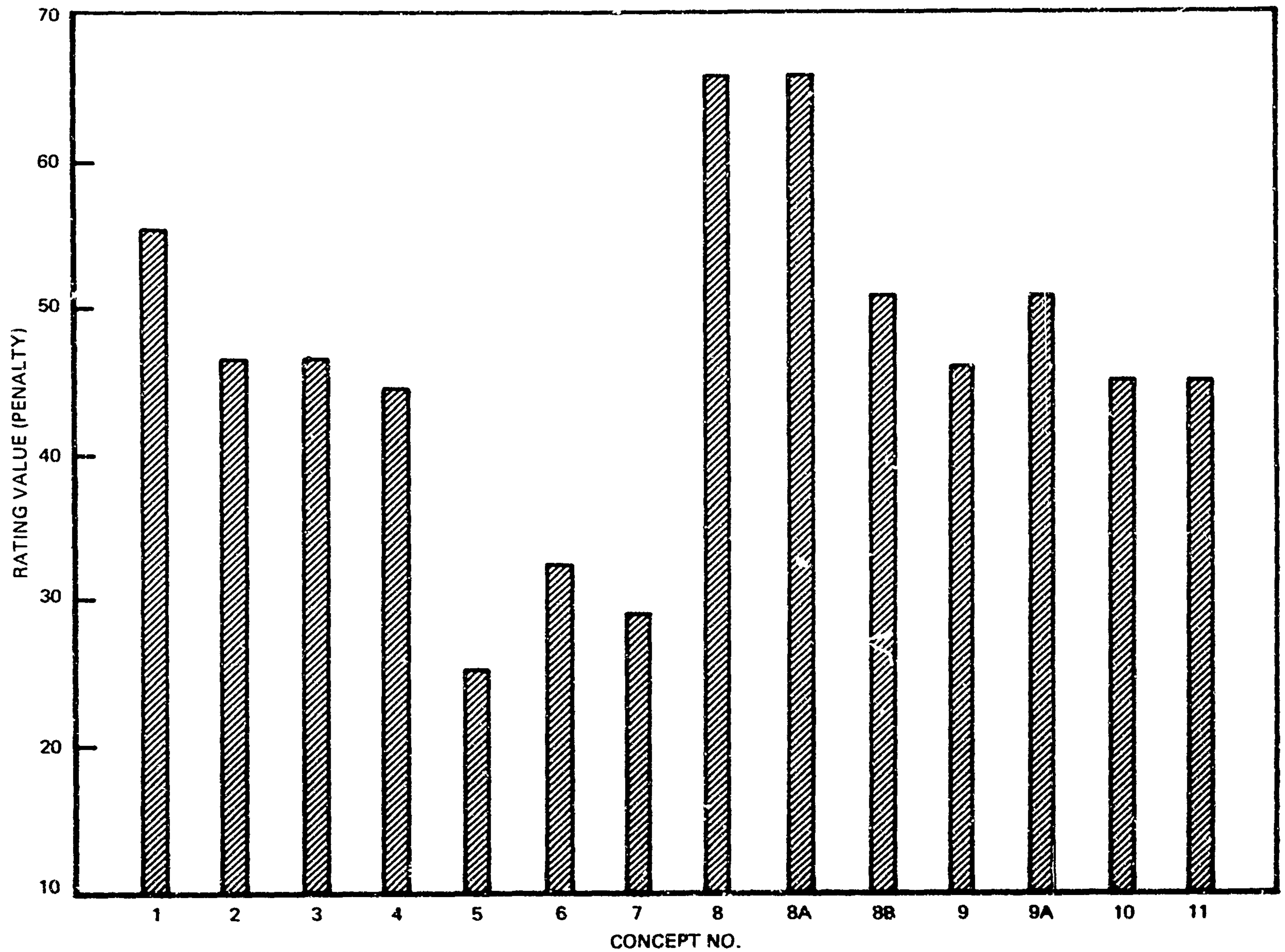

Figure 26. Effect of Two Power Source Loss on System Performance

evaluation is related to a vulnerability analysis in that the rating value is related to the size of critical subsystems. Concept No. 1 has a rating value of 1.000, since all subsystems powered both critical and noncritical functions. Concept Nos. 2, 3, and 4 had a value of .934, and Concept No. 6 had a value of .668. The remaining systems had a value of zero, indicating complete isolation of critical and noncritical functions.

c. Performance Rating Value

The results of the four evaluations were normalized and combined with weighting factors applied to each evaluation rating, resulting in the performance rating value. These weighting factors were:

System Efficiency	40%
Loss of Two Power Sources	30%
Function Isolation	20%
Loss of One Engine	10%

System efficiency was weighted heavily, since it is the most significant factor affecting the performance of the airplane under normal operation. The second parameter, loss of two power sources, is important because it is associated with the emergency mode of operation. The last parameter, loss of one engine, can be defined also as the loss of a single subsystem. It is weighted lightly, because such a loss only places the system in the intermediate mode of operation. The results of this evaluation were reversed to relate a high performance rating with a low penalty. These results are shown in Figure 27. Concept Nos. 5 and 7 ranked the highest, since they required low input power and contained maximum isolation. Concept No. 3 was rated low primarily because of the high power input requirements. The baseline, Concept No. 1, had a low rating due to its high penalty when two power sources were lost and the absence of function isolation.

7. SYSTEM COST

Initial investment costs derived for each system include costs of hardware material, assembly, installation and checkout, armorplate (Concept No. 1A only), and initial spares. These cost elements are used to determine ten-year system costs and total ten-year costs. System components are assumed to be within the state-of-the-art in the 1970 to 1980 time period. Costs of hardware have been estimated on this basis. All costs are in 1970 dollars.

a. Method

Initial investment costs for hydraulic system hardware have been developed from purchasing history and records maintained by VAD, cost estimating relationships derived from these records, and budgetary

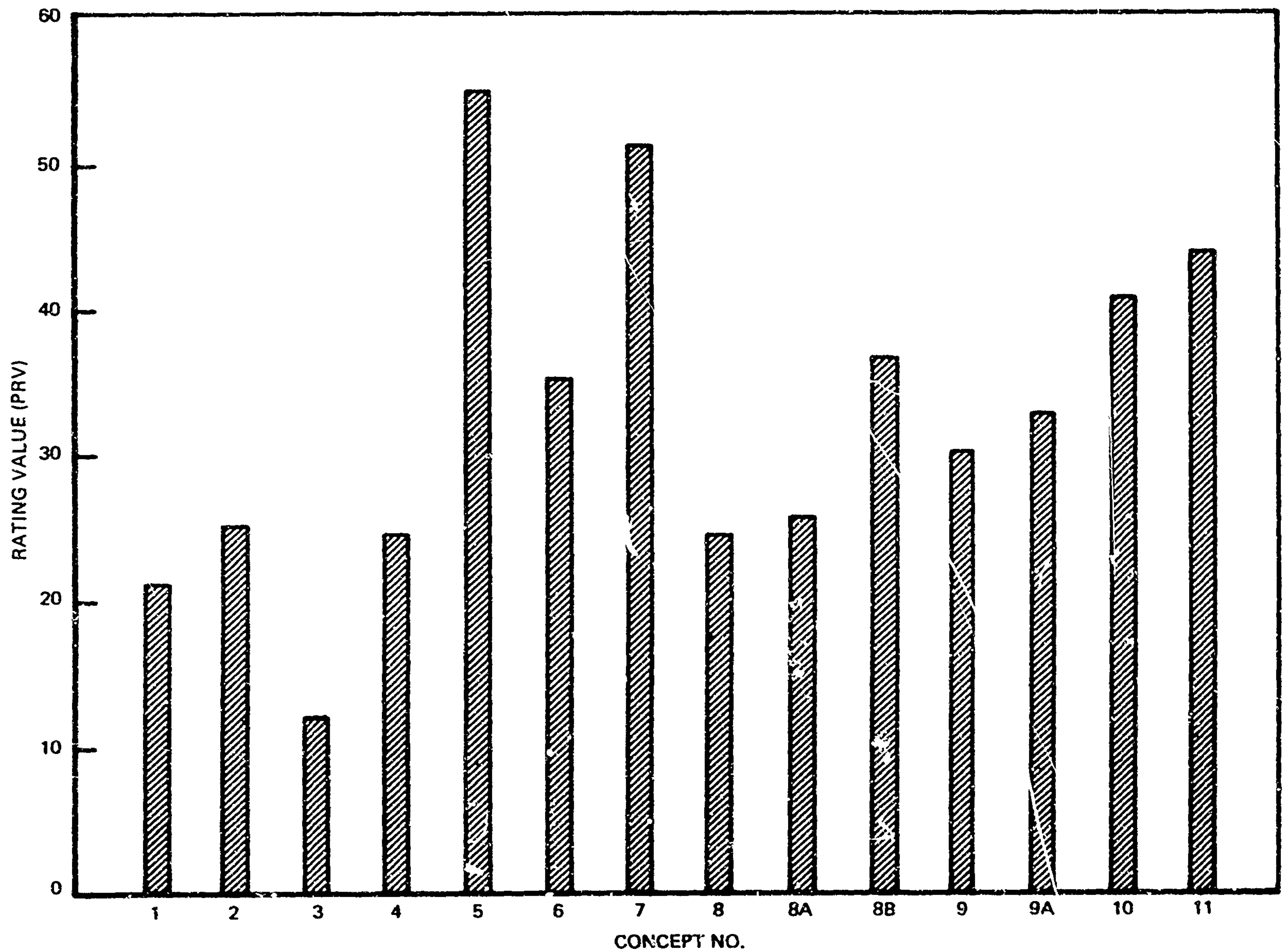

Figure 27. Performance Rating Value

quotes from vendors. Only costs of major components such as pumps, reservoirs, accumulators, actuators, filters, valves, motors, tubing, etc., described in concept packages, have been estimated. Estimates include hardware material costs, assembly, installation and checkout, and material handling. These costs are adjusted by an empirical factor related to the reliability of the baseline hydraulic system. This factor accounts for costs of a difference in reliability for a particular system with respect to the baseline. Equation for this factor, RCF, is:

$$RCF = .061/(1/MTBF)^{.545}$$

where MTBF = actual mean-time-between failure in hours for system components.

All hydraulic system hardware material and labor costs are considered constant for quantities greater than 1,000 units (learning curve percent slope equal to 100). A factor of two times hardware material cost has been used to account for labor to assemble, install, and checkout each system. Hardware cost ranges for the various types of components used in this study are contained in Appendix V.

b. Results

Summary of initial investment costs is shown in Table XXXI. These costs include, in addition to the hydraulic system, the cost of armorplate and initial spares. Lowest cost system is the modified pulsating flow system (Concept No. 8A), and the highest cost is the electrohydraulic power package system (Concept No. 9). Factors influencing initial investment costs in addition to hardware components cost are survivability and system operational reliability, which are reflected in the initial quantity of systems required. Low cost of the modified pulsating flow system is attributed to low cost of hardware components (assumed as state-of-the-art) and high survivability (negligible attrition rate). High cost of the electrohydraulic power package system is primarily the result of high cost hardware components.

c. Cost Rating

Systems are rated on the basis of total ten-year hydraulic system cost rather than total ten-year system cost. As total system cost (aircraft with hydraulic system) is dependent upon parameters from all the other evaluation areas, these parameters are considered in the ratings established for each system by these other areas. Thus, duplication of considerations in the cost rating is avoided by using the total ten-year cost for the hydraulic system. Cost ratings are the dollar values of the total ten-year hydraulic system cost in billions of dollars for each system. Lowest rating number corresponds to lowest cost hydraulic system. Cost ratings are shown in Table XXXII.

TABLE XXXI HYDRAULIC SYSTEM INITIAL INVESTMENT COST SUMMARY

(Costs in Billions)

CONCEPT NO.	INITIAL QUANTITY	COST ELEMENT			
		HARDWARE AND INSTALLATION	ARMOR	INITIAL SPARES	TOTAL
1A	1338	.065	0.008	.010	.083
1	1074	.058	0.0	.002	.060
2	1122	.081	0.0	.005	.086
3	1207	.158	0.0	.017	.175
4	1132	.134	0.0	.009	.143
5	1207	.088	0.0	.009	.097
6	1083	.075	0.0	.003	.078
7	1141	.083	0.0	.006	.089
8	1348	.079	0.0	.013	.092
8A	1275	.046	0.0	.006	.052
8B	1286	.063	0.0	.009	.072
9	1353	.166	0.0	.028	.194
9A	1316	.073	0.0	.011	.084
10	1199	.088	0.0	.009	.097
11	1161	.073	0.0	.006	.079

TABLE XXXII COST RATINGS

CONCEPT NO.	COST RATING
1A	.230
1	.512
2	.377
3	.448
4	.261
5	.201
6	.174
7	.189
8	.200
8A	.135
8B	.163
9	.334
9A	.181
10	.205
11	.206

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SECTION VIII

TEN-YEAR SYSTEM COSTS

1. INTRODUCTION

Results obtained from system evaluation are used to determine ten-year system costs. Two different costing methods have been used. One method uses cost equations to estimate costs for each system. The second method uses cost deltas from a baseline total ten-year system cost. In the latter method, the cost equations are used to establish the total ten-year system cost deltas from the baseline system. The cost deltas result from an incremental change to preselected variables.

Ten-year costs are developed for the system and for the total aircraft system. Ten-year costs for each system are used to establish rating of systems on the basis of these costs only. These ratings are used in the value rating method, described in Section IX, which is an independent method used to establish the relative worth or value of the various systems defined in Section VI.

In determining total system costs, significant variables in the areas of survivability/vulnerability, reliability, maintainability, and hydraulic system performance have been used. For costing, probability of survival derived for the baseline system has been adjusted to correspond to the probability of survival required to attain an attrition rate of two aircraft per 1,000 missions in the emergency mode condition. Operational reliability and probability of survival are used to determine initial quantity of aircraft and systems required. Emergency mode reliability and adjusted probability of survival are used to determine attrition rate. Maintenance manhours per flight hour and number of maintenance actions per 1,000 flight hours for each system are used to establish maintenance associated costs. Horsepower drain from the engines resulting from the power required to operate each system is used to determine additional engine thrust required. Thrust is used to establish engine costs associated with the additional thrust required to overcome the horsepower drain.

2. TOTAL SYSTEM

a. Cost Equation

Total system costs are estimated using equations developed over a period of years at VAD. Equations have been modified to fit the ground rules of this study. Estimating equations are contained in Appendix V. Costing factors used for the hypothetical aircraft are shown in Table XXXIII. Costs included are initial investment (recurring only) for the complete aircraft and ten years of operation.

Initial investment costs for the aircraft are estimated using the aircraft characteristics specified in Table XXXIII. All of these characteristics are the same for each system, except for weight empty less system and system plus ordnance weight. Both of these vary as system weight varies. Aircraft initial investment costs are reduced by the amount of the initial investment cost for each system, so that total ten-year cost for each system may be estimated.

Operating costs are estimated using the operating cost factors from Table XXXIII and the aircraft initial investment costs. The aircraft mission required that 1,000 Unit Equipped (UE) aircraft be available at any time during a ten-year period to drop a bombload equivalent to 0.3 of the design gross weight of the aircraft during one mission of an hour and a half duration. Additionally, the aircraft will be utilized to perform missions on an average of 35 hours a month. The combat attrition rate (aircraft losses from hits in the hydraulic system) has been assumed to be 2 aircraft per 1,000 missions.

The mission requirements determine the amount of ordnance payload that must be dropped over a ten-year period.

The ten-year payload mission is derived as follows:

Missions per year per aircraft = (Aircraft Utilization)(12 Months)/Hours per Mission

= (35 hr/mo)(12 mo)/1.5 hr/Mission)

= 280

Payload per mission per aircraft = 0.3 (Design Gross Weight)

= 0.3 (45,000 pounds)

= 13,500 pounds

Ten-year payload mission per 1,000 aircraft = (10 Years)(Missions per year)(Payload per Mission)(1,000 Aircraft)

= (10)(280)(13,500)(1,000)

= 37.8 $(10)^9$ pounds

= 18.9 $(10)^6$ tons

b. Cost Delta

This method selects a baseline system from which costs are to be varied. Total ten-year system cost deltas are estimated using the estimating equations given in Appendix V. For the areas of survivability/vulnerability, reliability, weight, maintainability, performance, and system cost, a variable is selected to be varied by a preselected incremental change to the baseline value of the variable. The baseline total ten-year system cost is redetermined as each variable is varied, one at a time, by its incremental change. The change in cost for each incremental variable change is used to determine the total ten-year system cost delta for all other systems. The variation in cost for a change in each variable value with respect to the baseline values of these variables is assumed to be linear.

This method has been applied twice, us: . two of the systems as baselines for the purpose of determining effect of choice of baseline on cost deltas. Results are presented in Appendix V.

3. RESULTS

Summary of initial investment and operating costs for ten years is contained in Table XXXIV for each system. The table shows that attrition has the widest variation in cost effect. The effect of attrition on system cost varies from 0 to 72 percent, depending upon the system. Hardware initial investment exhibits 11 to 51 percent effect on system cost. Pay and allowances show 11 to 48 percent effect. Modified pulsating flow system (Concept No. 8A) is lowest in system cost, which is attributed to low state-of-the-art hardware costs and high survivability. The baseline system (Concept No. 1) is the highest cost system. This is attributed to low survivability of the system.

Summary of initial investment and operating costs for ten years for each total system is presented in Table XXXV. This table shows, again, that attrition has the most significant effect on cost, varying from 0 to 69 percent of total system cost. Less significant effects are initial investment (12 to 40 percent), depot maintenance (1.2 to 3.8 percent), and pay and allowances (5 to 17 percent). On a total system cost basis, the electrohydraulic backup system (Concept No. 6) exhibits the lowest cost. This is attributed primarily to system weight, which directly influences costs of initial investment and operation. In developing total system costs, system weight is traded off against ordnance weight. This trade-off establishes the number of aircraft required to drop 0.3 of the design gross weight in ordnance. As system weight for Concept No. 6 is relatively low, the net result of the trade-off is that fewer aircraft are required to accomplish the ten-year mission. Also, high survivability for this system results in low attrition costs. The

baseline system (Concept No. 1) is highest in total system cost, which is attributable to low system survivability, which is reflected in the cost of attrition. In this concept, attrition represents 69 percent of the total system cost.

Total system costs are shown in Figure 28. Effects on total ten-year system costs as attrition rates, monthly flight hours, and ordnance weight vary are shown in Figures 30, 31, and 32 respectively for the baseline system (Concept No. 1) and in Figures 33, 34, and 35 respectively for the three-hydraulic system (Concept No. 2). As attrition rate is varied, a corresponding change in probability of survival is made. Ordnance weight is varied by system weight. Since the sum of these two weights is a constant 14,744 pounds for all systems, a trade-off is made between ordnance and system weight.

Attrition curves for both systems in Figures 29 and 32 are virtually identical. These indicate that total ten-year system costs are extremely sensitive for attrition rates greater than 0.2 aircraft per 1,000 missions. For the systems studied, adjusted attrition rates vary from 0 for the electrohydraulic power package system to 2 aircraft per 1,000 missions for the baseline system. Total system costs range from approximately $8 to $25 billion for electrohydraulic backup and the baseline system respectively.

The curves for total system cost variation with flight hours per month shown in Figures 30 and 33, although not identical, are similar in shape and slope. The baseline system is the lower of the two curves. Both indicate that total system cost is sensitive to the monthly flying rate, as all other costing parameters remain constant. The variances in cost are influenced primarily by operating costs with significant influence attributed to attrition.

Total system cost variations with varying ordnance weight shown in Figures 31 and 34 are similar in both shape and slope, with the baseline system being the lower of the two curves. Since the combination of ordnance and system concept weight is constant for all systems, ordnance weight increases as system weight decreases. This has the effect of decreasing the number of aircraft required to perform a given mission and results in reducing total system cost of the operating life of the system. This decrease in cost is attributed directly to the number of aircraft required, since attrition rate remains constant.

A comparison of attrition with flight hours and ordnance variables indicates that total system cost is most significantly influenced by attrition. In addition, effects of attrition are included as flight hours and ordnance weight are varied. These studies show that of the variables considered, attrition rates significantly influence total system cost.

TABLE XXXIII

COSTS FACTORS

A.	Postulated Aircraft Characteristics	
	1. Gross Weight (Pounds)	45,000
	2. Weight Empty - Less Hydraulic System (Pounds)	30,256
	3. Hydraulic System Plus Ordnance Weight (Pounds)	14,744
	4. Number of Engines	2
	5. Ultimate Load Factor	8
	6. Design Mach Number	2.0
	7. Combat Ceiling (Feet)	40,000
	8. Fuel Consumption (Gallons per Hour)	500
B.	Operating Costs	
	1. Maintenance Manhours per Flight Hours (Aircraft Less Hydraulic System)	16
	2. Crew Ratio	1.55
	3. Force Size (Unit Equipped Aircraft)	1,000
	4. System Operational Life (Years)	10
	5. Aircraft Utilization (Hours per Month)	35
	6. Aircraft Attrition - (Aircraft/1,000 Missions)	2
	7. Mission Time (Hours per Aircraft)	1.5
	8. Ten-Year Payload Mission - Tons Delivered	$18.9\,(10)^6$

Table XXXIV. Hydraulic System Cost Summary (Billions of Dollars)

CONCEPT NUMBER	1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
NO. SYSTEMS REQUIRED – INITIAL	1074	1338	1122	1207	1132	1207	1083	1141	1348	1275	1286	1353	1316	1199	1161
INITIAL INVESTMENT															
SYSTEM	.058	.065	.081	.158	.134	.088	.075	.083	.079	.046	.063	.166	.073	.088	.073
ARMOR PLATE	0.0	.008	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPARES	.002	.010	.005	.017	.009	.009	.003	.006	.013	.006	.009	.028	.011	.009	.006
OPERATING COST															
BASE MAINT MATERIAL	.006	.007	.008	.017	.014	.009	.008	.008	.009	.005	.007	.018	.008	.009	.008
DEPOT MAINT	.014	.017	.020	.040	.033	.022	.018	.020	.021	.011	.016	.044	.019	.022	.018
GSE REPLACEMENT AND MAINT	.003	.004	.005	.010	.008	.005	.004	.005	.005	.003	.004	.011	.005	.005	.004
POL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OTHER EQUIP. REPLACEMENT AND MAINT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BASE INSTLS AND FACILITIES REPLACEMENT AND MAINT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SUPPLIES AND GENERAL SERVICES	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PAY AND ALLOWANCES	.059	.059	.061	.062	.059	.063	.061	.062	.073	.064	.064	.067	.065	.063	.062
REPLACEMENT TRAINING AND TRAVEL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TRAINING ORDNANCE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FREIGHT	.003	.001	.002	.002	.001	.000	.000	.000	.000	.000	.000	.000	.000	.000	.001
ATTRITION	.367	.059	.195	.142	.003	.005	.005	.005	.000	.000	.000	.000	.000	.009	.034
TOTAL COST	.512	.230	.377	.448	.261	.201	.174	.189	.200	.135	.163	.334	.181	.205	.206

Table XXXV. Total System Cost Summary (Billions of Dollars)

CONCEPT NUMBER	1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
NO. SYSTEMS REQUIRED – INITIAL	1036	1166	1060	1100	1065	1101	1041	1069	1166	1133	1138	1171	1153	1097	1078
INITIAL INVESTMENT															
AIRCRAFT	3.098	3.373	3.169	3.279	3.197	3.284	3.114	3.192	3.452	3.376	3.384	3.498	3.447	3.273	3.205
ARMOR PLATE	0.0	.008	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPARES	.610	.672	.623	.641	.622	.648	.611	.628	.688	.672	.673	.694	.686	.646	.632
OPERATING															
BASE MAINT MATERIAL	.297	.325	.304	.317	.308	.316	.300	.306	.333	324	.326	.338	.332	.315	.309
DEPOT MAINT	1.312	1.473	1.346	1.404	1.357	1.403	1.319	1.358	1.492	1.448	1.454	1.509	1.481	1.398	1.368
GSE REPLACEMENT AND MAINT	.174	.190	.179	.186	.181	.185	.175	.180	.195	.191	.191	.199	.195	.184	.180
POL	.251	.282	.256	.266	.258	.266	.252	.259	.282	.274	.275	.283	.279	.265	.261
OTHER EQUIP. REPLACEMENT AND MAINT	.057	.064	.058	.060	.058	.061	.057	.059	.065	.062	.063	.065	.064	.060	.059
BASE INSTLS AND FACILITIES REPLACEMENT AND MAINT	.218	.245	.224	.233	.224	.233	.220	.226	.253	.241	.243	.251	.246	.233	.229
SUPPLIES AND GENERAL SERVICES	.136	.153	.140	.146	.140	.146	.137	.141	.158	.151	.151	.156	.153	.145	.143
PAY AND ALLOWANCES	1.237	1.385	1.272	1.327	1.269	1.329	1.249	1.287	1.455	1.373	1.381	1.431	1.400	1.324	1.302
REPLACEMENT TRAINING AND TRAVEL	.339	.381	.347	.361	.348	.362	.341	.351	.388	.373	.375	.387	.380	.360	.354
TRAINING ORDNANCE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FREIGHT	.150	.040	.070	.039	.021	.020	.021	.021	.021	.021	.021	.021	.021	.022	.030
ATTRITION	17.389	2.467	6.651	2.470	.062	.160	.191	.170	.000	.000	.000	.000	.000	.273	1.263
TOTAL COST	25.268	11.058	14.639	10.729	8.045	8.414	7.986	8.178	8.782	8.506	8.537	8.832	8.684	8.498	9.335

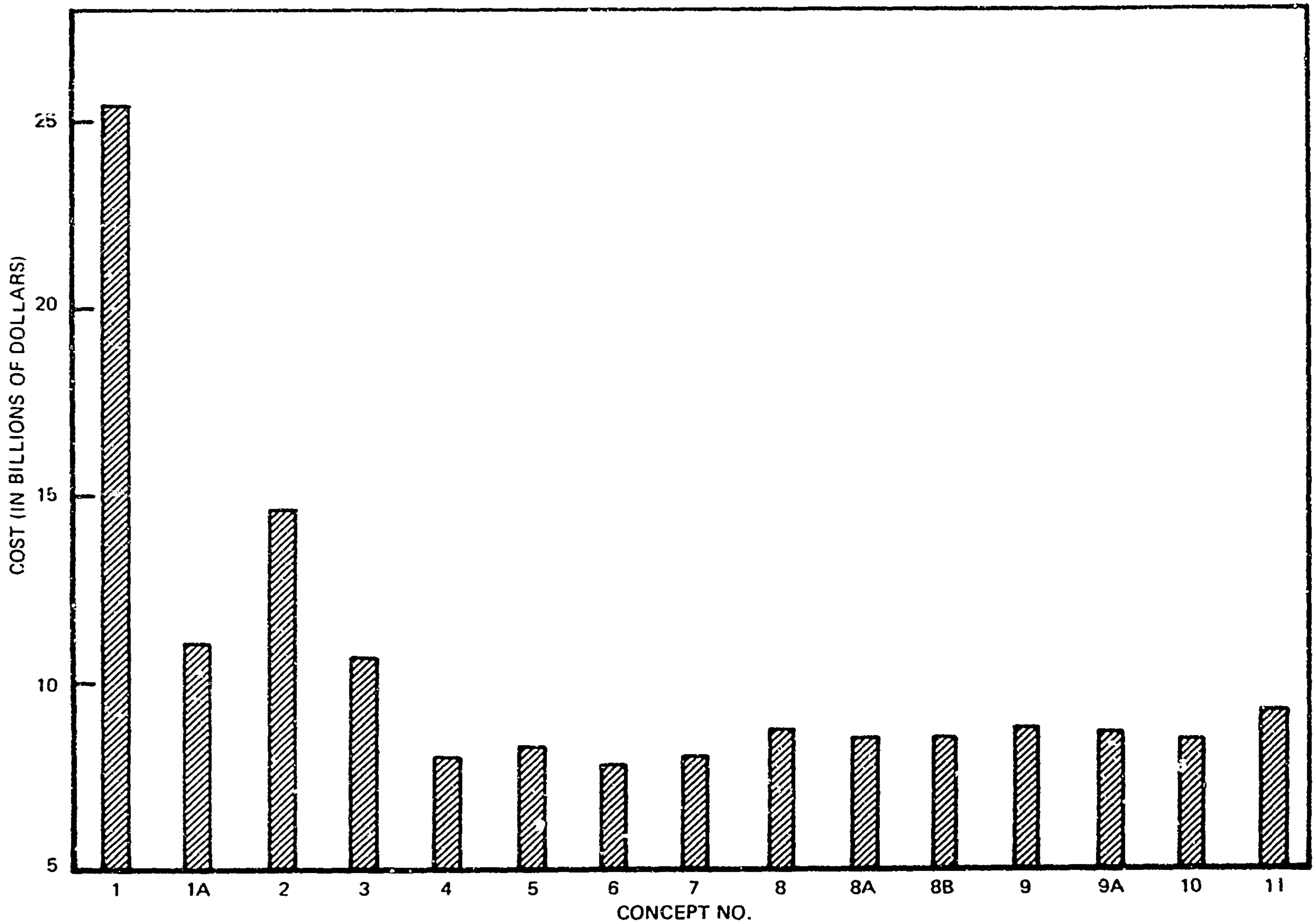

Figure 28. Total Ten-Year System Cost

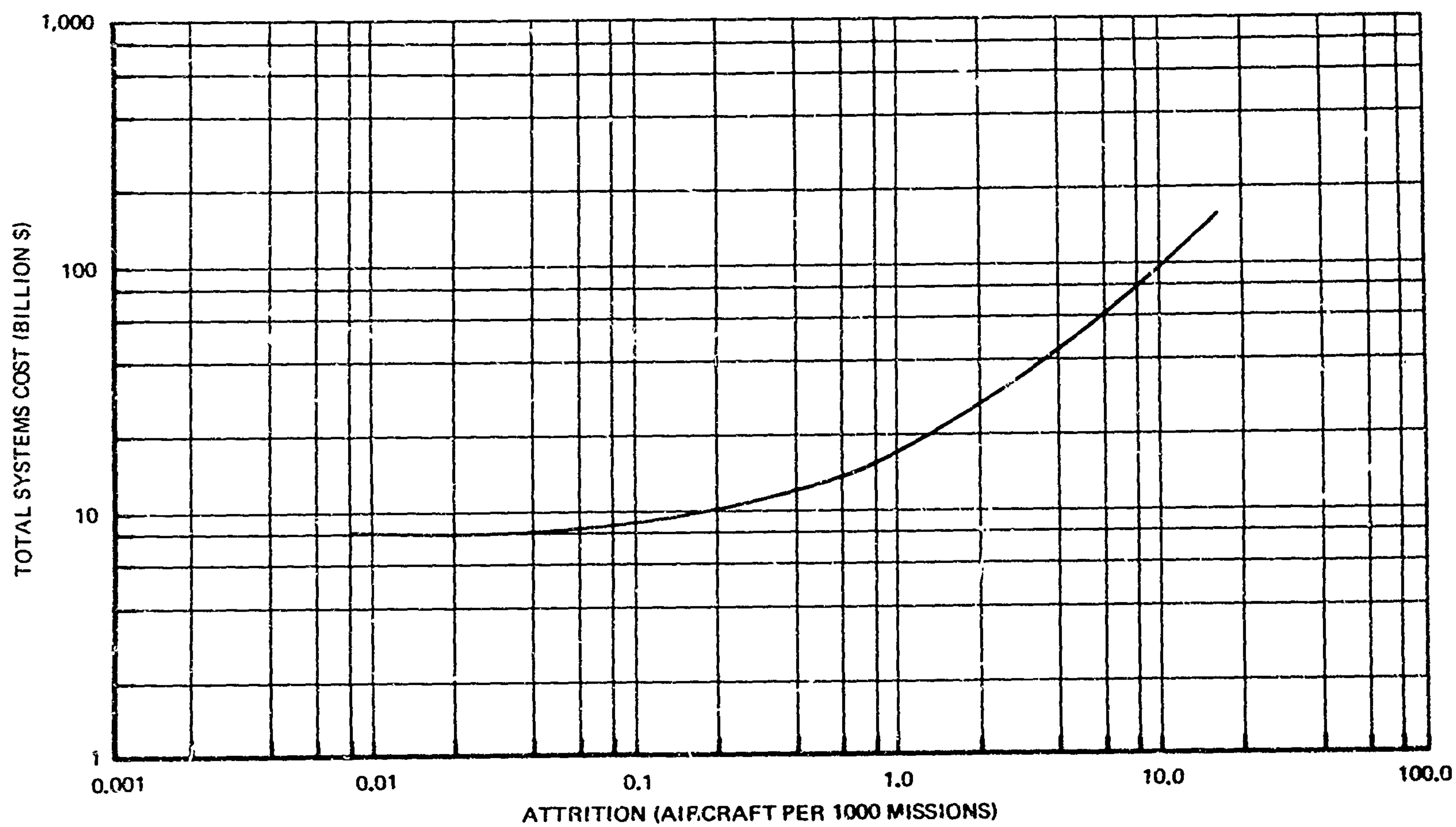

Figure 29. Attrition Cost – Concept No. 1

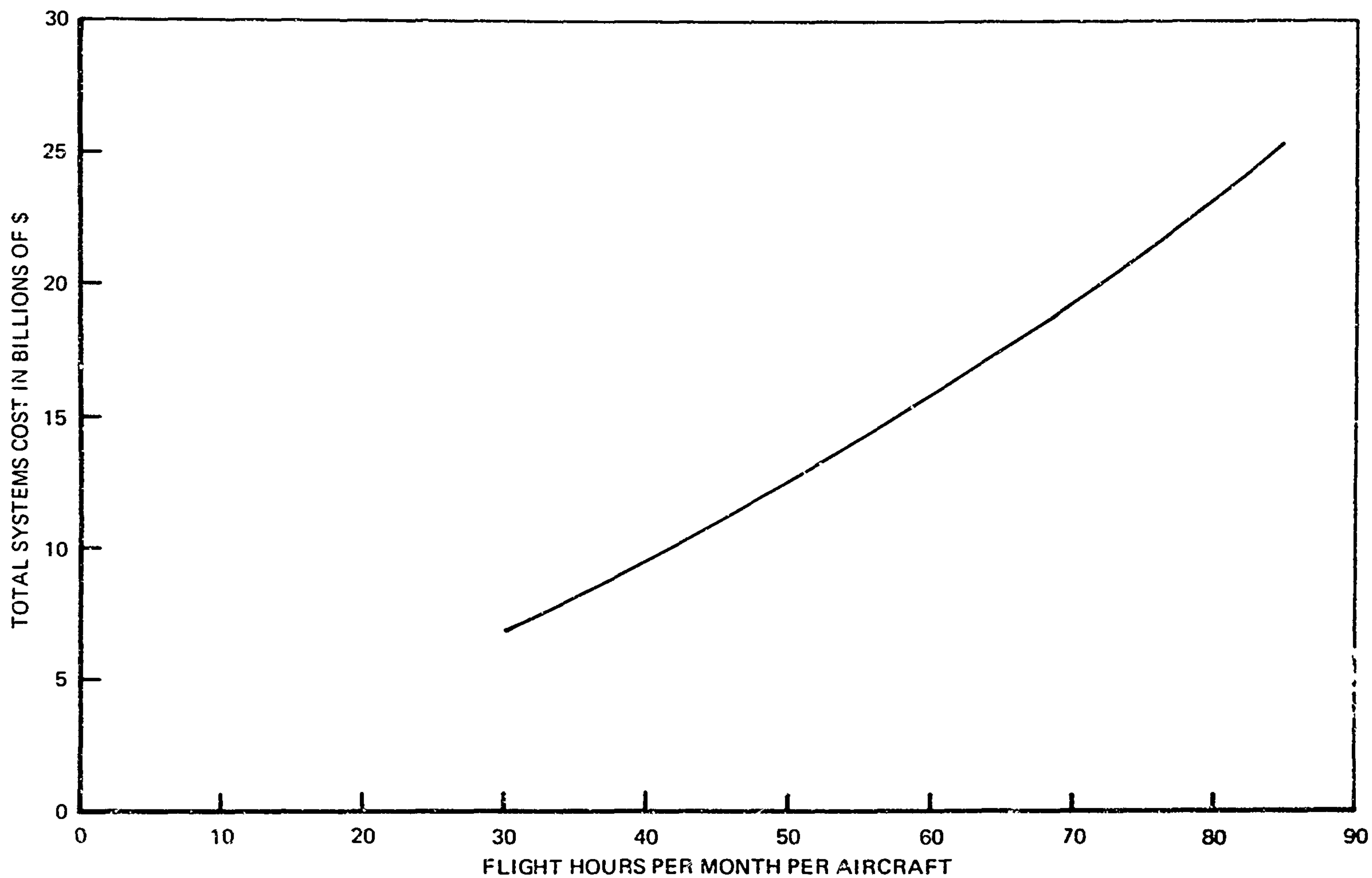

Figure 30. Monthly Flight Hours Cost -- Concept No. 1

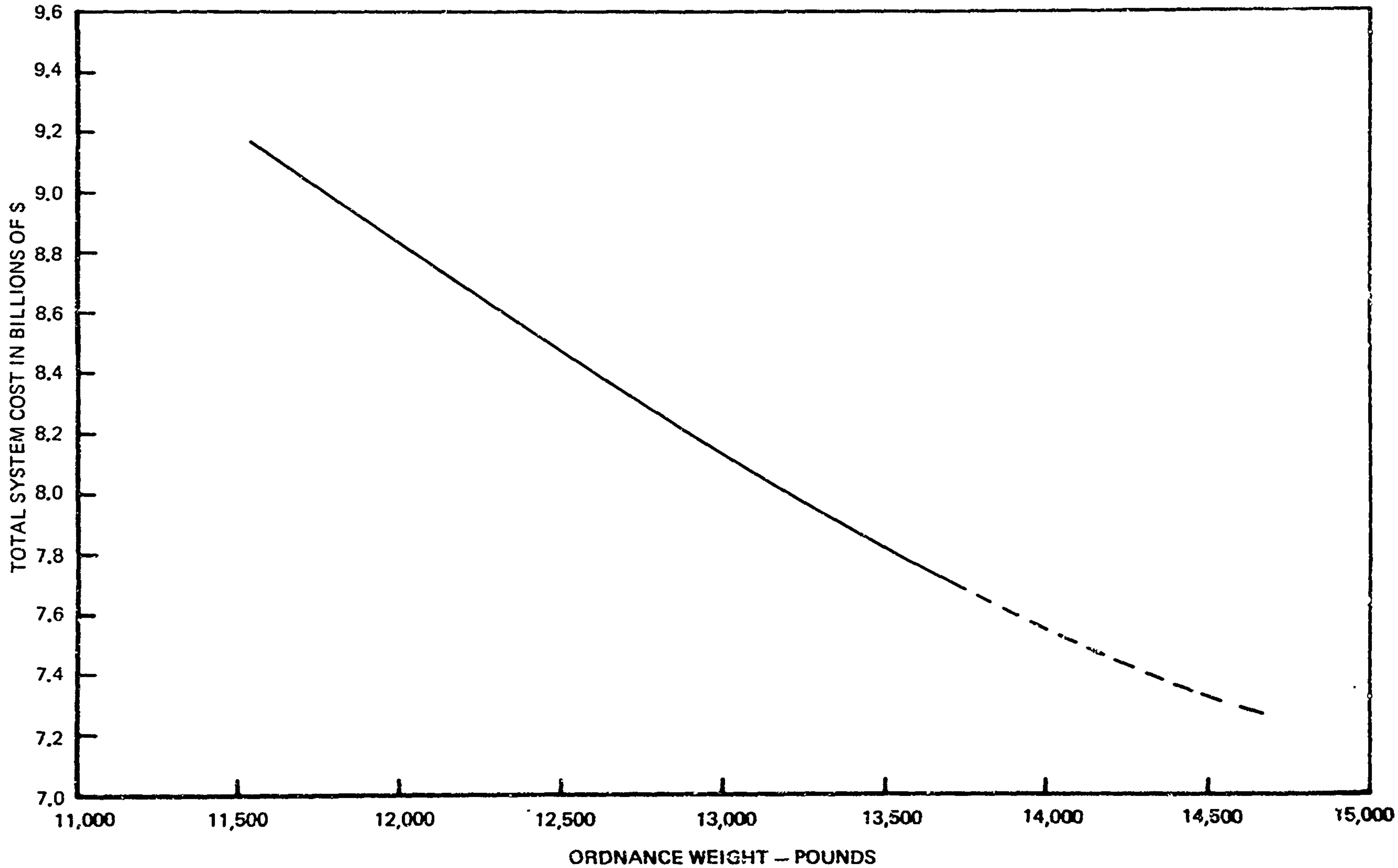

Figure 31. Ordnance Weight Cost – Concept No. 1

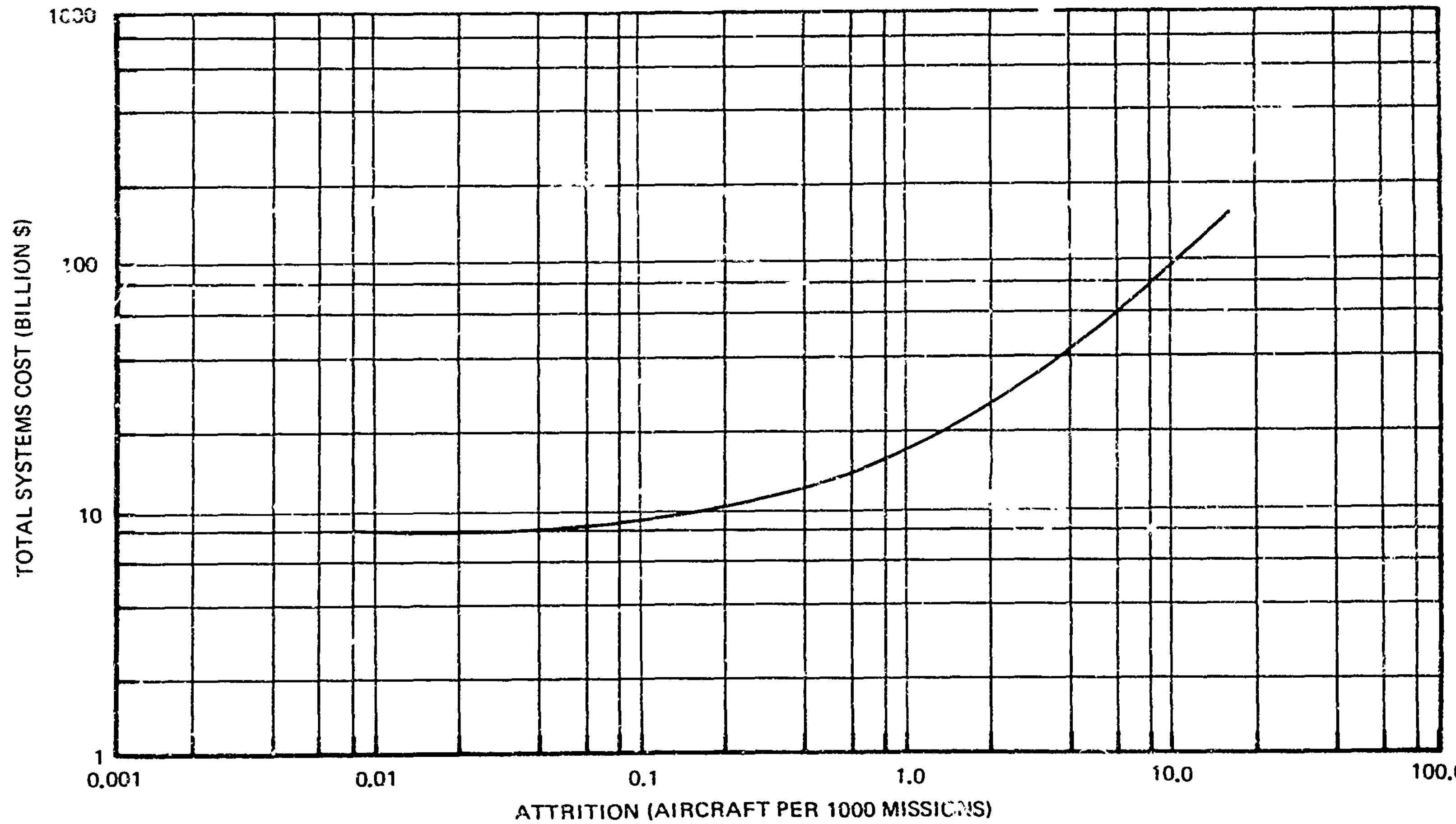

Figure 32. Attrition Cost – Concept No. 2

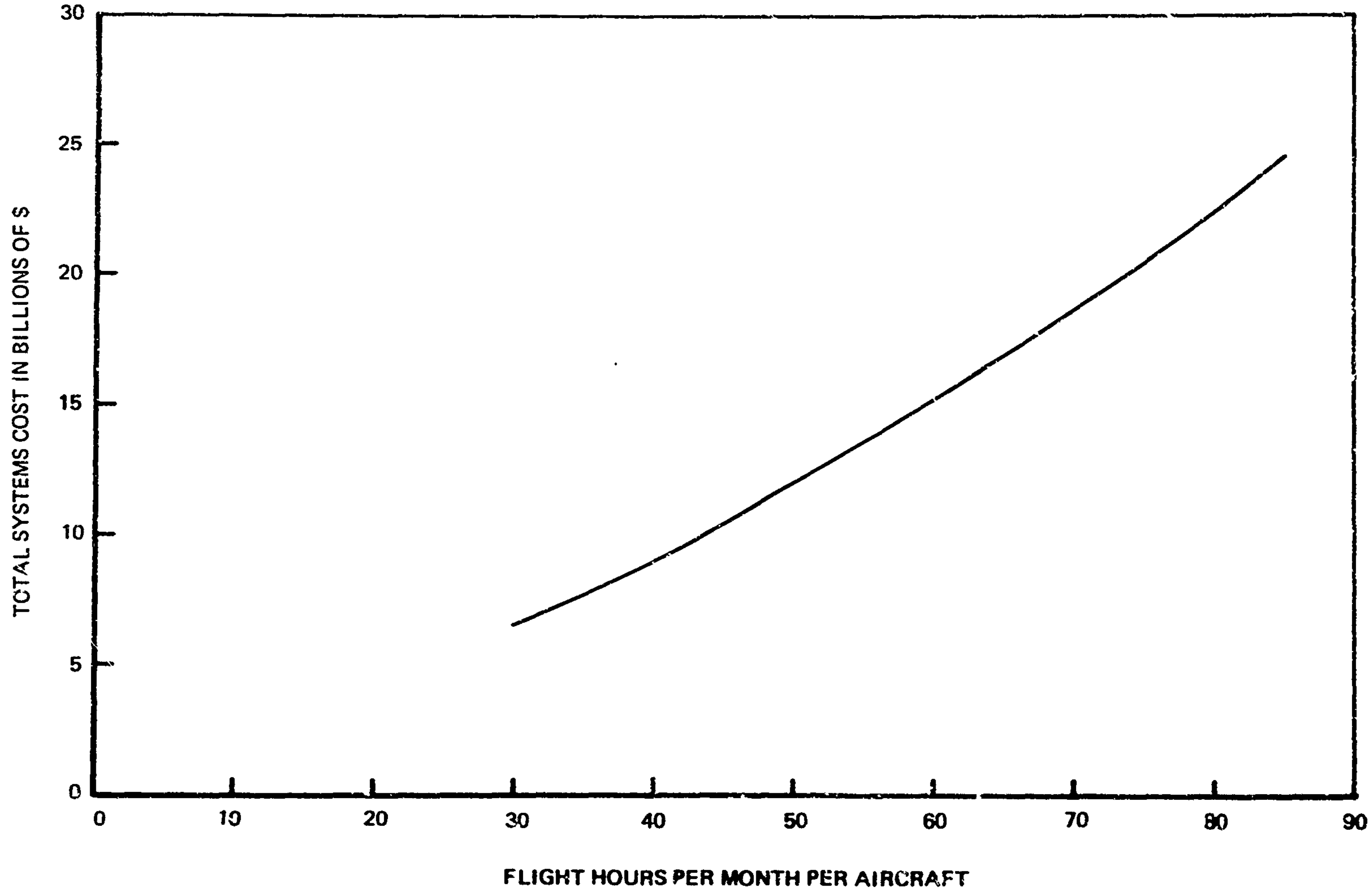

Figure 33. Monthly Flight Hours Cost – Concept No. 2

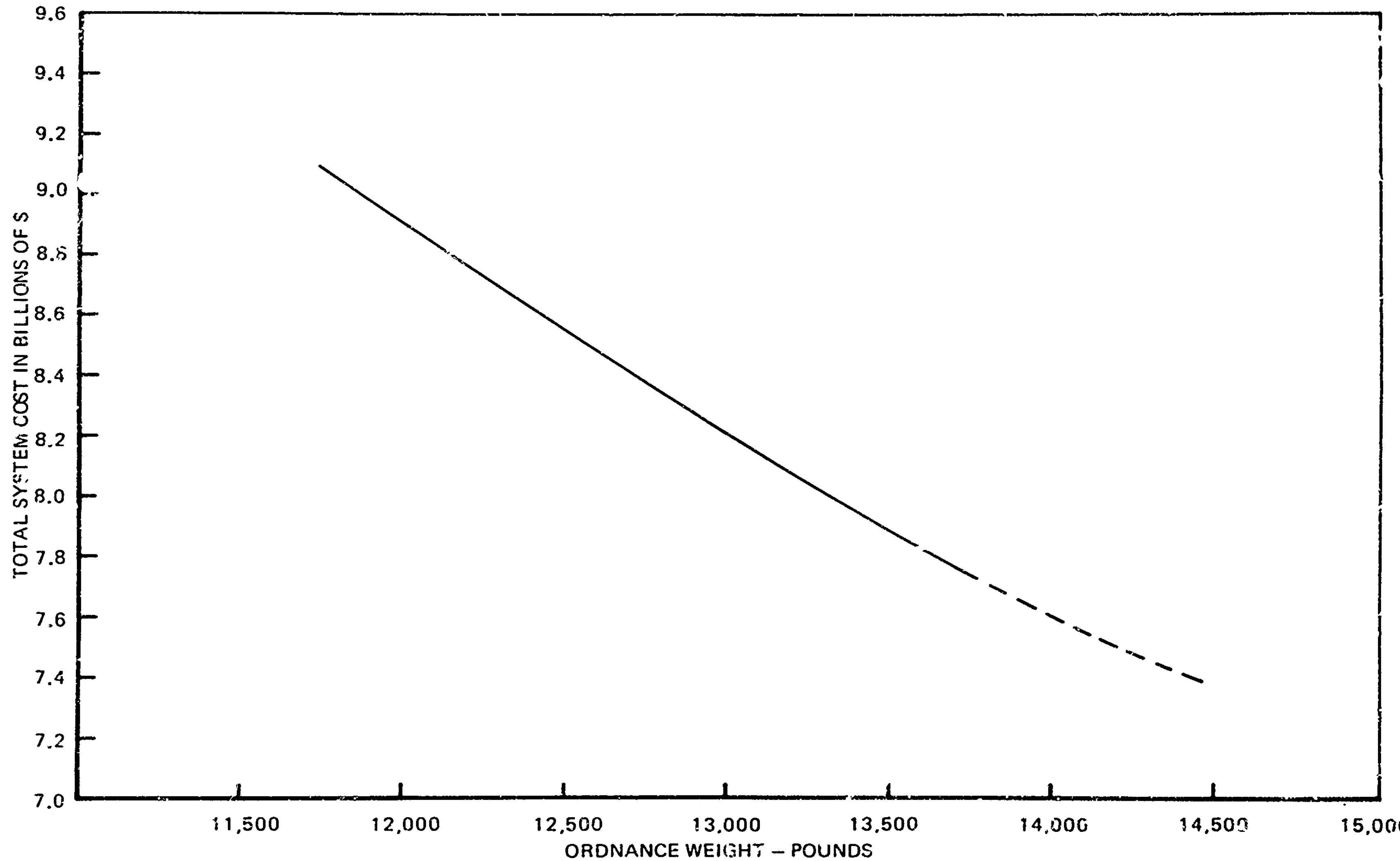

Figure 34. Ordnance Weight Cost – Concept No. 2

The cost delta method is used to develop the cost change from system to system as related to the baseline system. These results are shown in Figure 35. Incremental changes are contained in Table XXXVI. All of the systems result in positive cost deltas from the baseline as shown in Figure 35. Electrohydraulic backup system exhibits the smallest positive delta cost, which is attributed primarily to low system weight in using the cost delta method. However, results from the study of effect of varying attrition rates (which may be correlated with probability of survival) show that variation of cost with attrition is not linear as assumed in the cost delta method. Therefore, in this method the effects of attrition on costs are minimized, when using probability of survival as a linear function parameter.

In Table XXXVI the incremental change in total system cost is negative for a $1 addition to system cost. The method used in computing costs results in a decrease in aircraft less system cost (CUA) corresponding to this increase in system cost (HUA). Since more cost elements use CUA as a variable, the combined effect on total system cost is negative.

Aircraft required for ten years of operation are based on having the number of initial investment aircraft available at the beginning of, and during, this ten-year period. Number of aircraft to absorb combat attrition and normal operation losses are added to the initial investment quantity to obtain the total number of aircraft for ten years. Breakdown of aircraft required is shown in Table XXXVII for each concept. Differences in total aircraft quantities between systems is attributed to attrition rates applicable to the various systems. Losses attributed to system operational reliability are relatively small, when compared to losses from attrition for Concept Nos. 1, 1A, 2, 3, and 11. Losses for all pulsating flow and electrohydraulic power package systems are attributed to operational reliability only.

The attrition rates are based on the probability of kill for each system adjusted to provide a rate of 2.00 for the baseline system. This results in the large spread in combat attrition losses. An actual analysis would consider all systems in the aircraft (hydraulic, electrical, fuel, etc.) resulting in attrition rates closer in value. However, in this study the vulnerable area was based on hydraulic system only. Applying more realistic values to attrition rates would result in a smaller spread in the aircraft losses between systems; however, the relative positions of systems would remain the same.

Costs and aircraft quantities associated with phasing the total ten-year system in and out of operation were not considered. Thus, aircraft quantities shown in Table XXXVII are the maximum requirements over a ten-year period. These quantities can be reduced by reducing aircraft availability requirements, especially during phasing out of the system.

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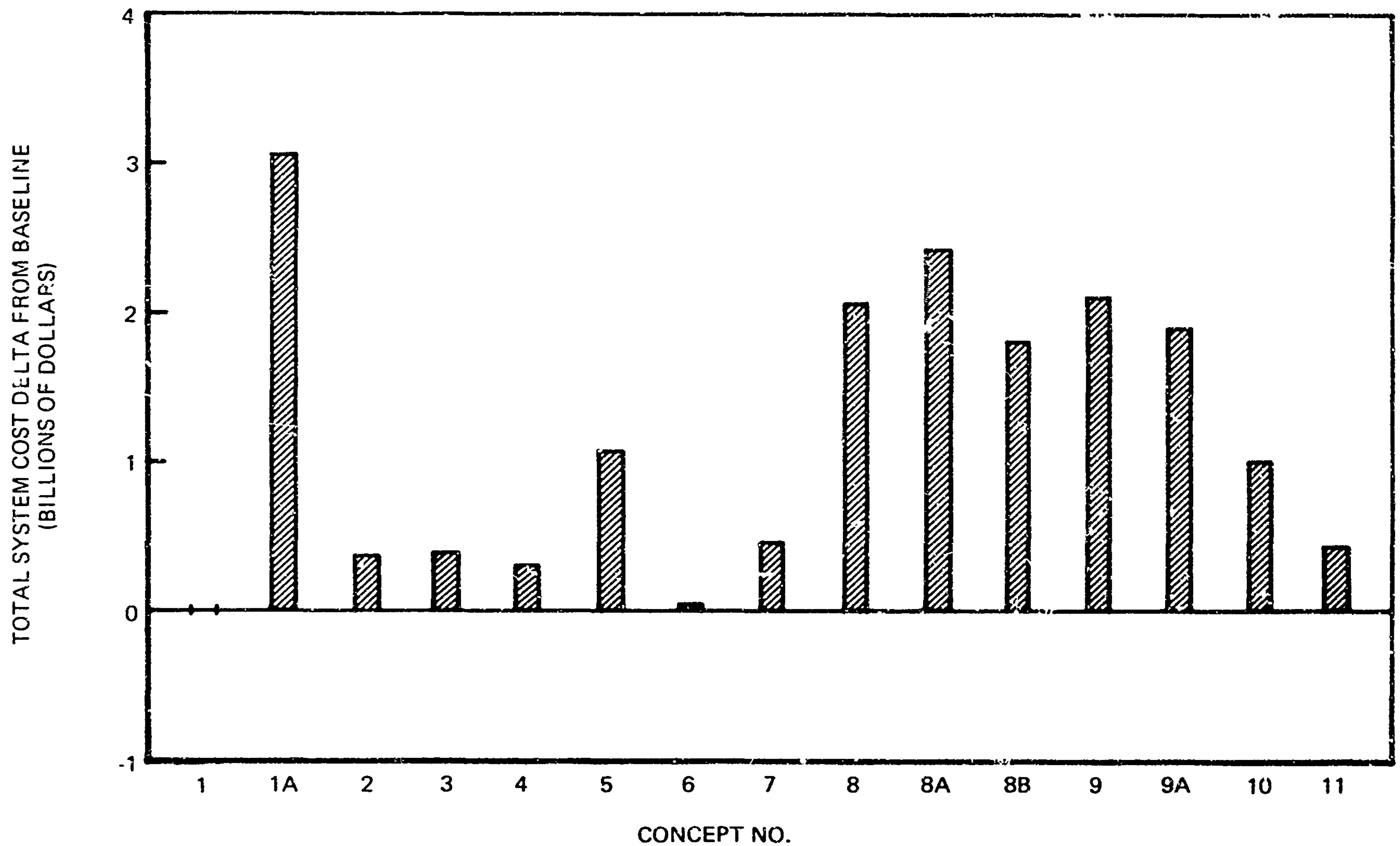

Figure 35. Total System Cost Variation from Baseline

TABLE XXXVI

INCREMENTAL COST CHANGES FOR BASELINE CONCEPT

PARAMETER	INCREMENTAL CHANGE	INCREMENTAL COST CHANGE (BILLIONS OF DOLLARS)[1]
Survivability	+.000001	-.000020480
Reliability	+.00705[1]	-.0052961
Maintainability	+1.0 Maintenance Man-hour per Flight Hour	+.2735900
Weight	+1.0 Pound	+.0020398
Performance	+1.0 Horsepower	+.0001925
System Cost	+1.0 Dollar	-.0000082

Note:

1 Reliability Incremental Change Based on 1-Hour Increase in Effective MTBF

TABLE XXXVII

AIRCRAFT REQUIRED FOR TEN-YEAR OPERATION

Concept	Initial Investment	Attrition Rate per 1,000 Missions	Combat Attrition Losses	Normal Operation Losses	Total Losses	Aircraft Required
1A	1,166	.260010	821	166	987	1,987
1	1,036	2.000000	5,600	36	5,636	6,636
2	1,060	.746700	2,129	60	2,189	3,189
3	1,100	.266380	774	100	874	1,874
4	1,065	.006934	20	65	85	1,085
5	1,101	.017272	51	101	152	1,152
6	1,041	.021838	62	41	103	1,103
7	1,069	.018971	54	69	123	1,123
8	1,166	0.	0.0	166	166	1,166
8A	1,133	0.	0.0	133	133	1,133
8B	1,138	0.	0.0	138	138	1,138
9	1,171	0.	0.0	171	171	1,171
9A	1,153	0.	0.0	153	153	1,153
10	1,097	.029610	86	97	183	1,183
11	1,078	.140130	399	78	477	1,477

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SECTION IX

VALUE RATING

1. INTRODUCTION

During system evaluations, each evaluation area establishes a rating number for each system based on criteria peculiar to that area. This results in a set of six rating numbers for each system. The value rating system combines each set of six numbers into a composite rating which is defined as the value rating number for the system. The highest rating a system may have is 100. This number indicates the best design a system may have within the criteria established for the evaluations. The system having the highest value rating number is considered to be the best overall system of the systems being evaluated. Thus, systems may be ranked by use of the value rating numbers.

Reliability rating values include considerations other than those required to develop operational and emergency mode reliability used in the costing equations. The rating indicates those components and systems expected to have the most problem areas from fabrication through service usage in addition to consideration of emergency, intermediate, and operational mode reliability.

Maintainability rating values reflect considerations other than maintenance manhours per flight hour or number of maintenance actions required. These two variables have been used in determining total system costs. Ratings include consideration of number of parts, operating temperatures, pressure, and speeds, access, AGE tools, scheduled maintenance, skills, and safety.

Performance rating values include consideration of system efficiency (reflected in the cost equations by additional engine thrust required to overcome horsepower drain from system operation), loss of two power sources, function isolation, and loss of one engine. Effects of the last three considerations are not considered in the costing equations.

Survivability, weight, and hydraulic system cost ratings are directly related to the parameter values of these variables.

Since value ratings reflect other considerations in addition to total ten-year hydraulic system costs, ranking of systems by the value rating method may not agree with rankings established only from total ten-year system costs.

2. METHODOLOGY

The value rating method is based on the theory that any aircraft system, from the component level through the total system level, has a function to perform, a weight, and a set of significant, measurable, and distinctive characteristics. These characteristics may be used to uniquely identify a set of systems. As function and weight are significant considerations in the design of any aircraft system, these two elements are emphasized in the value rating method. Sets of characteristics are chosen to represent function and weight respectively. Since all characteristics selected are measurable, each is converted into a positive characteristic number. This number is a measure in percent of the nearness that the value of the characteristic is to the best or most desirable value a characteristic may have. All characteristic numbers associated with function are summed, as are those for weight. The product of these two sums are divided by the sum of all characteristic numbers to obtain an unadjusted value rating number. This number is adjusted by a factor so that the best value rating any system may achieve is 100. A detailed description of the value rating method and its application to this study is contained in Appendix VI.

3. RESULTS

Value ratings determined for each system are presented in Table XXXVIII. Highest rated system is the electrohydraulic backup (Concept No. 6), and the lowest rated system is the baseline with armor (Concept No. 1A). System weight is attributed to having the greatest effect on these two value ratings; Concept No. 6 has a relatively low weight, and Concept No. 1A has the highest weight of all systems evaluated.

TABLE XXXVIII

SYSTEM RATINGS

Concept	Value Rating
1	35.38
1A	18.72
2	42.96
3	34.61
4	42.73
5	38.10
6	45.10
7	44.95
8	22.87
8A	31.64
8B	31.31
9	24.89
9A	28.95
10	36.52
11	38.65

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SECTION X

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

This study program identified systems potentially immune to disastrous failure when subjected to small arms ground fire. These systems were examined in terms of cost/effectiveness. No system could be singled out as the best system, since the methods of definition and evaluation had much latitude. Conclusions were then drawn from an overall examination relative to types of systems and significance of evaluation results.

Redesigning the baseline system by adding redundancy with isolation or backup features results in greater survivability than can be obtained by adding armorplate to protect vulnerable or critical areas. Maximum survivability is achieved by isolation and separation of vulnerable areas into smaller areas or subsystems. This is evident by the high survivability shown for the systems using pulsating flow and electrohydraulic power packages. Slightly less survivability is achieved with backup methods.

Results from system evaluation were used to develop the total ten-year system cost, cost delta from the baseline system, and value rating for each system. These values for each system are tabulated and ranked in Table XXXIX with lowest costs and highest value ratings ranked at the top. Cost equation ranking is of primary importance with the other rankings providing added confidence. An examination of the variance of the rankings with respect to the cost equation ranking provided confidence in identifying the five systems in Table XXXX as the best systems for overall cost/effectiveness. Since each of the five systems had high survivability, the other rating values were more significant in establishing this ranking. The electrohydraulic backup system (Concept No. 6) ranked high, since weight and cost were significant factors in the development of delta cost rankings. The electromechanical backup system (Concept No. 4) ranked second, due to its high reliability and maintainability ratings, although offset with lower performance and cost ratings.

System evaluation results in assigning specific values to survivability/vulnerability, maintainability, reliability, performance, weight, and cost variables. A change in any one or more of these values would be the result of redefining the system. The cost delta method assumes no change in system definition, since incremental changes are made to variable values one at a time. This method is used to show the significance of incremental changes on total system delta cost for the various systems. The cost delta method indicates that weight,

hydraulic system cost, and maintainability have the greatest effects on the total cost delta, with system weight having the greatest effect. System performance exhibits the least effect.

2. RECOMMENDATIONS

Confidence in the rankings of Tables XXXIX and XL is dependent on the latitude of system definition and evaluation. This latitude is dependent on knowledge of the principles applied in the system definition and on related experience. A recommended program based on the five systems in Table XL may overlook other promising systems for the reasons above. The objective of this and subsequent programs is to prove feasibility of selected systems and to gain confidence in the selections for aircraft application. Since most of the systems had higher probabilities of survival than the armor-plated baseline, they were examined further in view of the above objectives. To meet these objectives, the level of technology of promising systems should be advanced so that further evaluations can be made with a high degree of confidence. This technology includes component development and development of hybrid systems using the best features of the systems defined in this program. Each promising system was examined for component development requirements and advantageous principles. Recommendations are as follows for component and/or system development.

a. The components for the systems in Table XL are in some stage of use or development with their feasibility proven. The principles of these systems should be applied to new system definitions and development.

b. The components of the pulsating flow system are currently in development. The principles of this system should be applied to new system definitions and development in view of its high survivability. An early application in a simulator or aircraft is recommended.

c. Automatic failure detection and isolation devices should be investigated due to limited new development. The use of these devices in a system is similar to the use of motorpumps (Concept No. 10) resulting in high survivability. The principles of this system should be applied to new system definition and development.

TABLE XXXIX CONCEPT RANKING SUMMARY

RANKING	VALUE RATING		COST EQUATION		COST DELTA	
	CONCEPT NO.	VALUE	CONCEPT NO.	DOLLAR VALUE	CONCEPT NO.	Δ DOLLAR VALUE
1	6	48.57	6	7.986	1	0
2	7	46.18	4	8.045	6	.04496
3	11	44.23	7	8.178	4	.33469
4	5	40.76	5	8.414	2	.35877
5	10	40.00	10	8.498	3	.39182
6	4	38.85	8A	8.506	11	.4485
7	8A	38.42	8B	8.537	7	.47425
8	8B	37.36	9A	8.684	10	1.00573
9	2	35.94	8	8.782	5	1.08923
10	9A	32.64	9	8.832	8B	1.84024
11	8	32.52	11	9.335	8	2.08674
12	1	31.58	3	10.729	8A	2.45578
13	3	28.47	1A	11.058	1A	3.06686
14	1A	25.33	2	14.639	9A	3.08562
15	9	24.08	1	25.268	9	3.54382

TABLE XL SELECTED CONCEPTS AND RATING VALUES

RANKING	CONCEPT NO.	NAME	RATING VALUE					
			**SURVIVABILITY	RELIABILITY	MAINTAINABILITY	WEIGHT	PERFORMANCE	COST
1	6	Electrohydraulic Backup	.993329	30.632	5.686	1,337*	64.10	.174*
2	4	Electromechanical Backup	.996095*	19.713*	5.033*	1,712	75.20	.261
3	7	Five Hydraulic Sources	.993753	27.681	6.127	1,540	47.90	.189
4	5	Flywheel Power	.994021	34.838	7.080	1,839	44.10*	.201
5	10	Motorpump Isolation	.992318	38.785	7.175	1,790	58.40	.205

* Indicates best rating value
** Values for probability of survival

SECTION XI

DEVELOPMENT PLANS

1. INTRODUCTION

This study program resulted in a ranking of all concepts based on three methods: total operating costs, cost deltas about the baseline concept, and value rating. The three rankings were compared, and selections were made for overall cost/effectiveness. An appraisal of the systems in the final ranking was made to determine recommendations for component and system development. The proposed program involves hardware development and system definition as applied to selected aircraft. The objective of this program is to prove feasibility of selected systems and to provide the necessary confidence level for aircraft applications. Component and systems for continued activity in this plan are listed in Section X.

2. PROGRAM DESCRIPTION

The development plan is divided into three phases and is an extension of the work reported herein. At the completion of the last phase, solutions derived during this program can be applied to production aircraft with a high level of confidence.

a. Concept Definition and Evaluation

The work accomplished and reported herein represents the activity prior to the development plan. Cost and survivability evaluations of defined systems form the bases for system selection for further definition and hardware for development. Those systems and major components which showed promise, yet lagged in technology advancement, were tentatively selected for development.

b. Phase I Component Development

Initially, current aircraft will be selected for application of the selected systems and components. The requirements used for designing components in the aircraft system will be compiled and used for component design in this phase. Testing component designs under simulated system conditions will prove feasibility and uncover problem areas. Results during this phase will influence system design in Phase II.

c. Phase II System Evaluation

The requirements used for designing components and systems in the selected aircraft will be compiled and used for system design in

this phase. The systems selected will form the basis for new system definition. Optimization and combinations of these systems will be considered; component design and tests of Phase I will influence system design. The designed systems and the current system in the aircraft will be evaluated regarding survivability, maintainability, reliability, performance, weight, and costs. Systems will be selected and further designed or modified for testing on a system evaluator. The evaluator will contain means for driving system power sources and for simulating critical functions under normal and emergency conditions. Each system will be evaluated for dynamic characteristics during normal operation and during subsystem failure.

d. Phase III Flight Test Evaluation

Initially, a current aircraft will be selected for the flight tests of this phase. A system selected from Phase II will be integrated with the aircraft system. The aircraft will have the capability of using its current system with provisions for switching in the additional system. Added confidence will be achieved through qualification tests of new components and ground tests of the installed system. Flight tests will further evaluate the performance of the additional system under actual flight and environmental conditions. Flight operations will be such that comparisons can be made between the normal aircraft system and the additional system.

3. PROGRAM MILESTONES

The schedule for Phases I, II, and III span 60 months, as shown in Figure 36. Key milestones and decision points shown are described below.

a. Milestone No. 1

Initially, aircraft will be selected for component development, system evaluation, and flight tests.

b. Milstone No. 2

System and component requirements will be compiled and documented.

c. Milestone No. 3

Initial component designs will be released for fabrication and testing and for use in system design (Phase II).

d. Milstone No. 4

Final component designs will be released.

e. Milestone No. 5

Development tests on components will be completed. Component selection and recommendations will be made for system design. A final report for Phase I will be prepared.

f. Milestone No. 6

System designs and evaluation will be completed. Systems will be selected for evaluator program.

g. Milestone No. 7

Redefinition of selected systems for compatibility with the system evaluator will be completed.

h. Milestone No. 8

Systems tests on the evaluator will be completed, and a selection will be made for flight test evaluation. A final report for Phase II will be prepared.

i. Milestone No. 9

The flight test system will be designed using the principles of the selected system.

j. Milestone No. 10

The complete system will be installed and serviced in the selected aircraft.

k. Milestone No. 11

Ground checkout and tests will be completed.

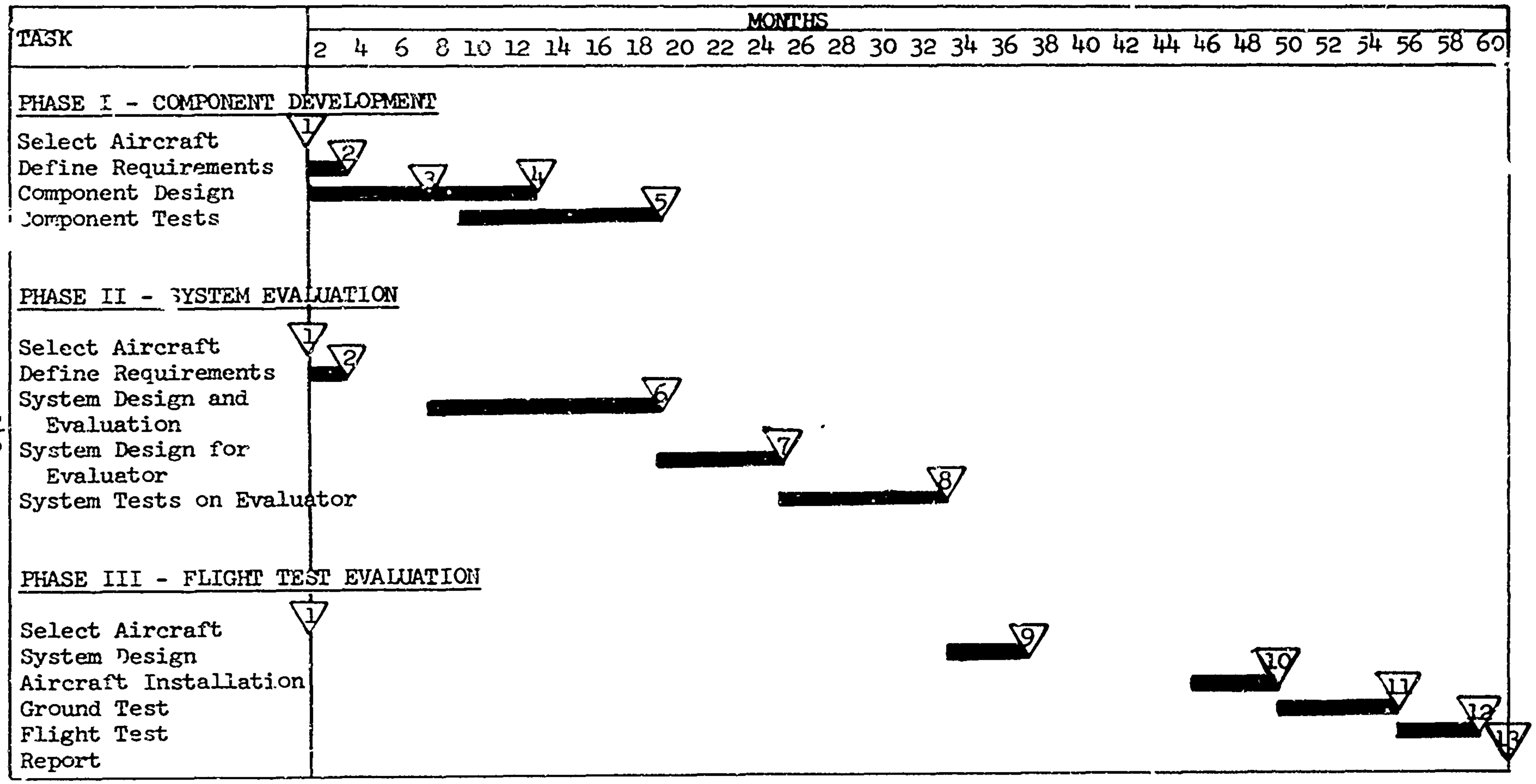
l. Milestone No. 12

Flight tests will be completed.

m. Milestone No. 13

A final report for Phase III will be prepared.

FIGURE 36. PROGRAM SCHEDULE



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1. North American Aviation, Inc., "Theoretical Study of Very High Pressure Fluid Power Systems," by D. W. Deamer and S. J. Brigham, NA66H-822, October 1966.

2. Republic Aviation Division, Fairchild Hiller, "Investigation of Pulsating Flow Hydraulic Concepts," AFAPL-TR-65-83, November 1965.

3. Military Standardization Handbook - Reliability Stress and Failure Data for Electronic Equipment, MIL-STD-217A, 1 December 1965.

4. Military Standard - Reliability Prediction, MIL-STD-765A, 15 May 1963.

5. "Navy Maintenance and Material Management Data for A-7A Airplane," Aeronautical Maintenance Management Information Center, Naval Air Technical Services Facility, Philadelphia, Pa., Cumulative Data for January-March 1967.

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APPENDIX I

CONCEPT DEFINITION DATA

1. SCHEMATIC DIAGRAMS

Each schematic diagram is in the form of a functional flow diagram relating each component to the power source. Defined components were limited to those that contribute directly to the generation, control, and utilization of power and those that require normal servicing. Components such as relief valves, ground connections, etc., were neglected in the definition. A list of symbols for the schematic diagrams is shown in Table XLI. Schematic diagrams are shown in Figures 37 through 49.

2. COMPONENT DATA

All components, including tubing and wiring, are listed in Tables XLII thr ·gh XLVI. Tabulated data include classification (i.e., critical or noncritical), pertinent physical and performance characteristics, and component quantites. These tables show the common components for all the systems. The total number of different components is 153; 58% of this number is common to two or more systems.

3. COMPONENT DESCRIPTION

The following are general descriptions of the components in Tables XLII and XLIII. All components are hydraulically operated unless otherwise indicated.

a. Primary Flight Control Actuators (Aileron, Rudder, and UHT)

These are linear, double-acting actuators (dual tandem for Concept Number 1) with internal valving, linkage, and porting to allow signal inputs by mechanical linkages from pilot stick and by electrical input from automatic flight control systems. These actuators for Concept Nos. 8, 8A, and 8B also contain integral three-phase rectifiers and spring-loaded accumulators for volume compensation.

b. Electromechanical Actuators (Aileron, UHT, Nose Gear Door, Main Gear Door, and Flaps)

These are reversible electromechanical actuators, each containing a ball screw, engaging clutch, and limit switches. The flight control actuators also contain feedback systems. Travel rates vary from .32 to 1.46 inches per second.

c. Air Refueling Actuator

This is a double-acting actuator with internal locks and position indicators on both ends. On Concept No. 8 this actuator also contains an integral two-phase rectifier, spring-loaded accumulator for volume compensation, and a solenoid selector valve.

d. Arresting Gear Actuator

This is a linear actuator containing a pneumatically charged accumulator for volume compensation and actuator extension (gear down). Hydraulic power is used to retract actuator. On Concept No. 8 this actuator also contains an integral single-phase rectifier and selector valve.

e. Nose Gear Steering Actuator

This is a linear actuator containing an integral electrohydraulic servo valve and electrical feedback. On Concept No. 8 this actuator also contains an integral single-phase rectifier and a spring-loaded accumulator for volume compensation.

f. Spoiler Actuator

This is a linear, double-acting actuator containing an integral mechanical servo valve for mechanical signal input. On Concept No. 8 this actuator also contains an integral three-phase rectifier and a spring-loaded accumulator for volume compensation.

g. Landing Gear, Flaps, and Speed Brake Actuators

These are linear, double-acting actuators. Internal locks are contained in the nose gear, main gear, and speed brake actuators. On Concept No. 8 (and Concept Nos. 8A and 8B for door actuators only), these actuators contain single- or two-phase rectifiers, spring-loaded accumulator for volume compensation, and solenoid selector valves.

h. Accumulator

This is a pneumatically charged, cylindrical, piston-separated accumulator.

i. Alternator Package

The alternator converts direct hydraulic flow into pulsating or alternating flow. The package contains an alternator valve, a hydraulic motor with integral flow control valve to drive the alternator valve, and a pulley box for a synchronizing belt interconnect with other alternators. The alternator valve has one inlet and three outlet pulsating flow ports. A rotating block mates with a stator plate to port inlet flow to the pulsating flow ports.

j. Automatic Failure Isolation Package

This package is used to isolate a portion of the system after damage has occurred. Two types of packages are used: one utilizes a selector valve for function selection and shutoff, and the other uses the valve for shutoff only. Both packages contain flow sensors, control logic, and the solenoid-operated selector or shutoff valve. The flow sensors transmit signals from supply and return lines to the control logic; these signals are proportional to flow. These signals are compared in the control logic, and any disparity beyond an acceptable limit will result in a signal to place the selector valve or shutoff valve in a position to close the hydraulic lines.

Other positions of the selector valve are obtained by pilot input to the control logic.

k. Brake Valve

This valve is power boosted, pedal operated.

l. Filter

The filter contains a stainless steel mesh element; rating is 15 micron absolute.

m. Flywheel Package

This package contains a rotary vane air motor; a flywheel; a variable delivery, pressure-compensated pump; an integral reservoir; and a 15-micron filter. Hydraulic pressure is 3,000 psig.

n. Generator Package

This package contains an AC generator and a connecting constant speed drive system.

o. Motorpump (Electric)

This package contains an AC motor, variable delivery or fixed displacement pump, and integral reservoir and filter. Operating pressure is 3,000 psi.

p. Motorpump (Hydraulic)

This package contains a fixed displacement motor, variable delivery or fixed displacement pump, and integral reservoir and filter. Operating pressure is 3,000 psi.

q. Pump

Pumps are engine driven, variable delivery, pressure compensated.

r. Rectifier Package

This package contains a one-, two-, or three-phase rectifier and a spring-loaded accumulator for volume compensation. The rectifier functions as parallel check valves to convert pulsating hydraulic flow to direct flow.

s. Reservoir

The reservoir is a cylindrical, piston-type, bootstrap design.

t. Selector Valve

These valves are multiport, multiposition, operated manually or electrically.

u. Transformer

The transformer is a cylinder with a piston and an integral bootstrap volume compensator on the outlet side. The transformer serves as a pressure converter and an isolator. All transformers used in these concepts have an area ratio of 1:1.

TABLE XLI Legend for Schematic Diagrams, Figures 37 Through 49.

TRANSMISSION LINES

- HYDRAULIC
- ELECTRICAL
- MECHANICAL

INTERFACES

1. MECHANICAL (CONTROLS)
2. MECHANICAL (MANUAL)
3. ELECTRICAL
4. PNEUMATIC (CHARGE)
5. PNEUMATIC (ENGINE BLEED)

COMPONENTS

AC	ACCUMULATOR	LL FLP	LEFT HAND INBOARD OR OUTBOARD LEADING EDGE FLAP ACTUATOR	NGS	NOSE GEAR STEERING ACTUATOR
L AIL	LEFT HAND AILERON ACTUATOR	RL FLP	RIGHT HAND INBOARD OR OUTBOARD LEADING EDGE FLAP ACTUATOR	PP_	POWER PACKAGE
R AIL	RIGHT HAND AILERON ACTUATOR	LT FLP	LEFT HAND TRAILING EDGE FLAP ACTUATOR	P	PUMP
L AT	LEFT HAND AILERON TAB ACTUATOR	RT FLP	RIGHT HAND TRAILING EDGE FLAP ACTUATOR	R	RECTIFIER-HYDRAULIC
R AT	RIGHT HAND AILERON TAB ACTUATOR	G	GENERATOR PACKAGE	RES	RESERVOIR
AR	AIR REFUELING ACTUATOR	HPS_	HYDRAULIC POWER SOURCE	RUD	RUDDER ACTUATOR
ALT	ALTERNATOR PACKAGE-HYDRAULIC	L MG	LEFT HAND MAIN GEAR ACTUATOR	SV	SELECTOR VALVE
AG	ARRESTING GEAR ACTUATOR	R MG	RIGHT HAND MAIN GEAR ACTUATOR	SOV	SHUTOFF VALVE
AFI C	AUTOMATIC FAILURE ISOLATION & CONTROL PACKAGE	L MGD	LEFT HAND MAIN GEAR DOOR ACTUATOR	SB	SPEED BRAKE ACTUATOR
AFI S	AUTOMATIC FAILURE ISOLATION & SHUTOFF PACKAGE	R MGD	RIGHT HAND MAIN GEAR DOOR ACTUATOR	L SPO	LEFT HAND SPOILER ACTUATOR
L BV	LEFT HAND BRAKE VALVE	MP E	MOTOR PUMP ELECTRIC DRIVEN	R SPO	RIGHT HAND SPOILER ACTUATOR
R BV	RIGHT HAND BRAKE VALVE	MP H	MOTOR PUMP HYDRAULIC DRIVEN	T	TRANSFORMER-HYDRAULIC
F	FILTER	NG	NOSE GEAR ACTUATOR	L UHT	LEFT HAND UNIT HORIZONTAL TAIL
FW	FLYWHEEL PUMP PACKAGE	NGD	NOSE GEAR DOOR ACTUATOR	R UHT	RIGHT HAND UNIT HORIZONTAL TAIL

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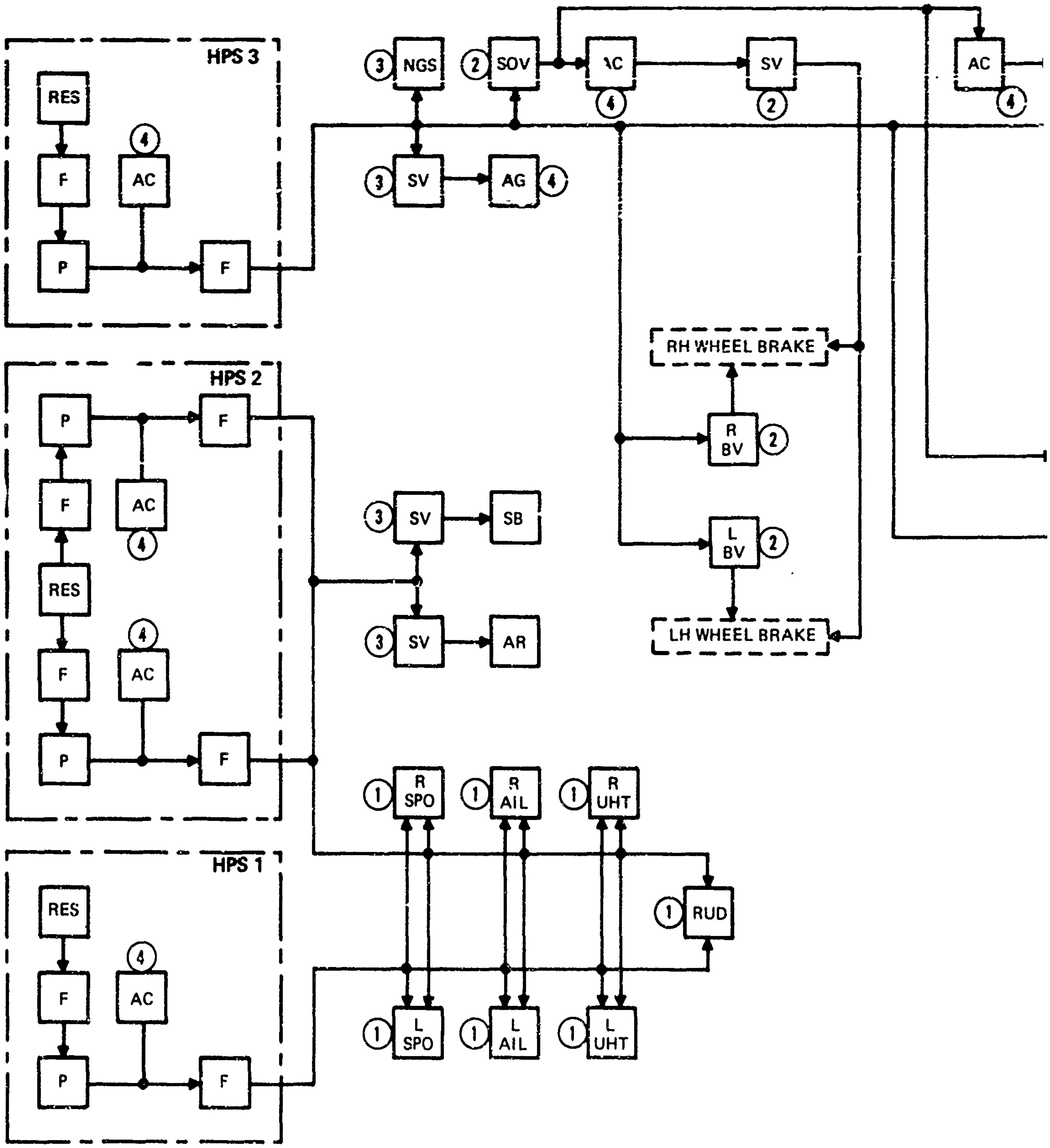

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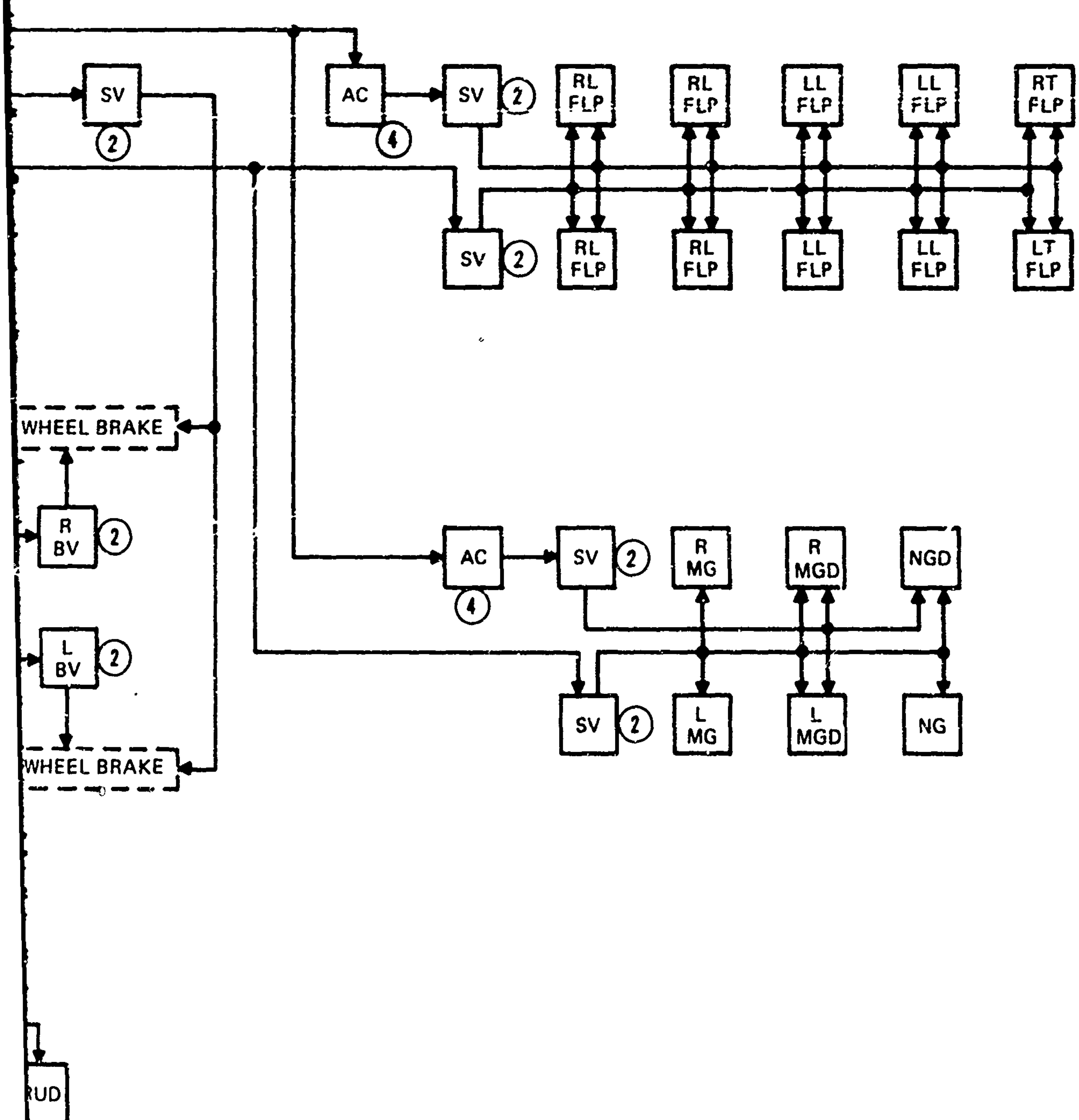

Figure 37. Concept No. 1 Baseline Schematic Diagram

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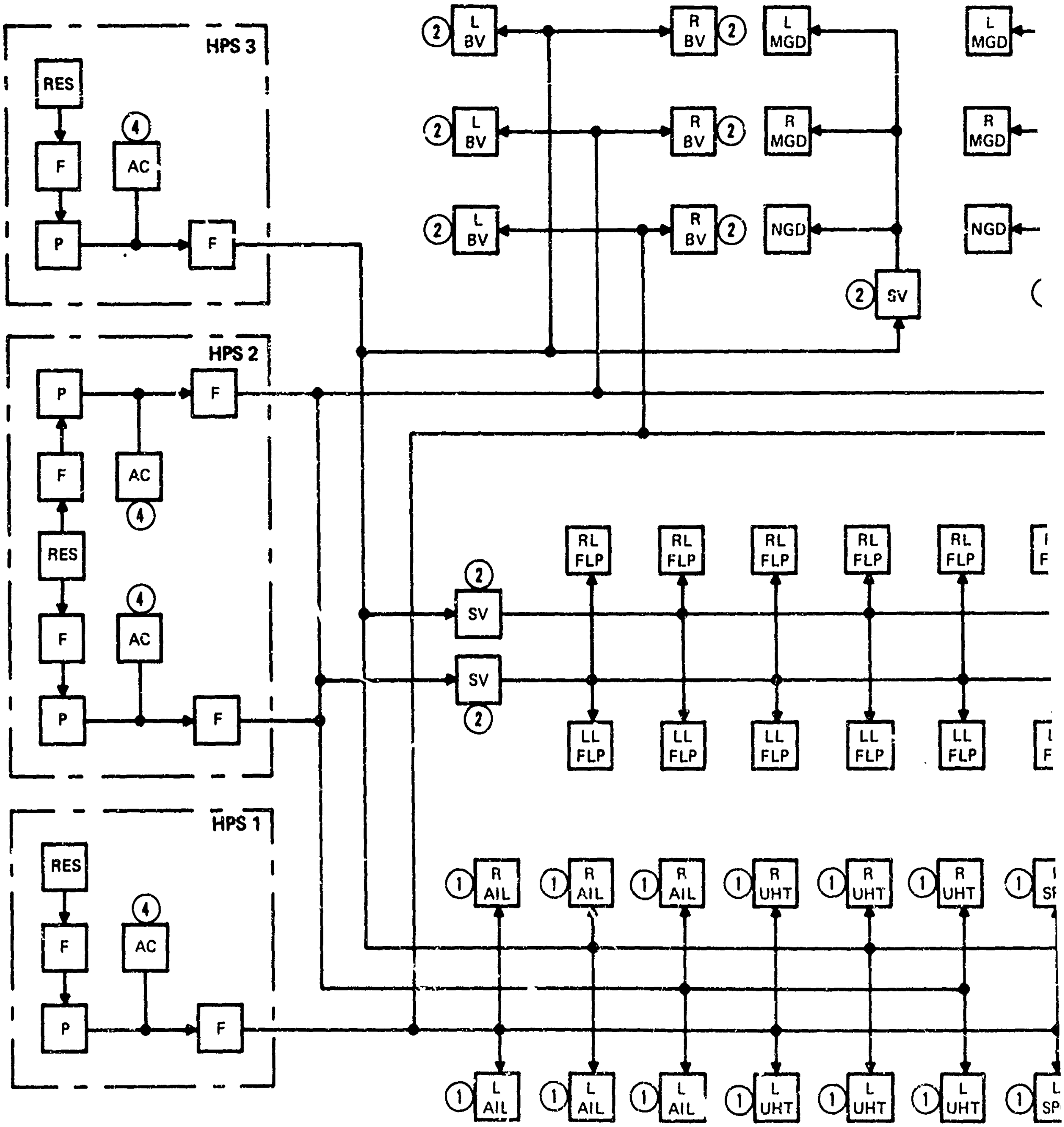

Figure 38. Schematic Diagram for Concept No. 2 Three Hydraulic Sources and Concept No. 3 High Pressure

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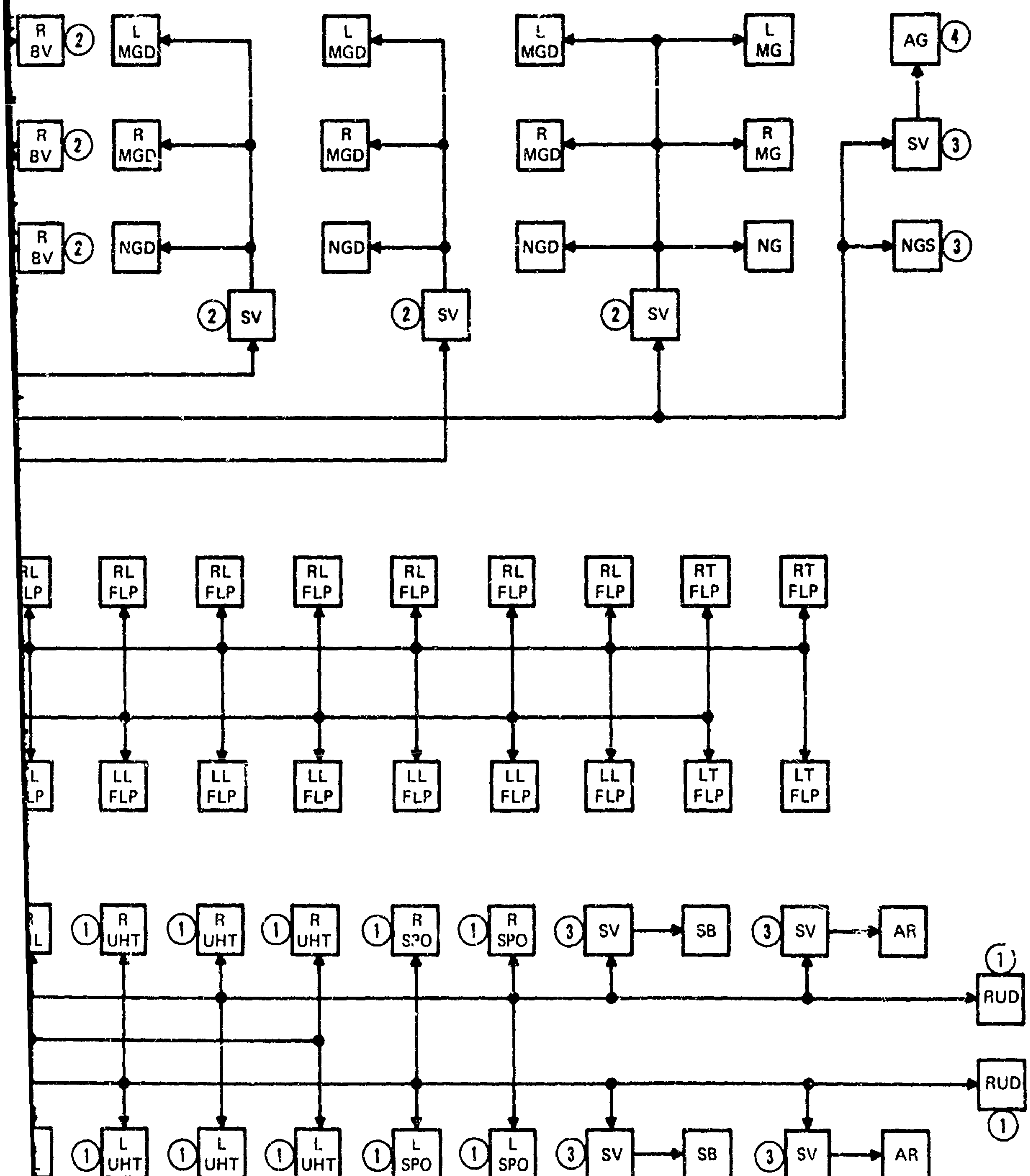

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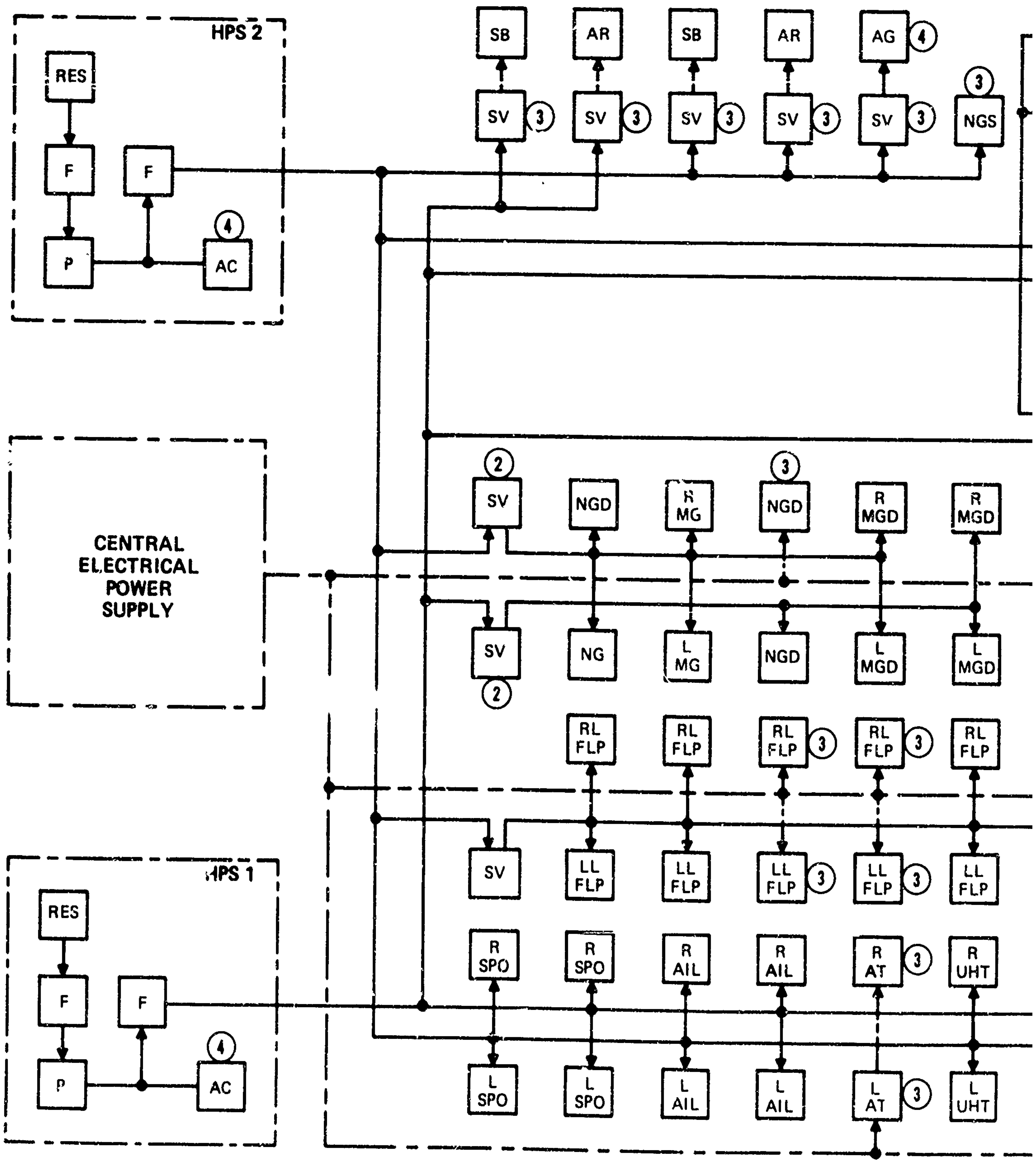

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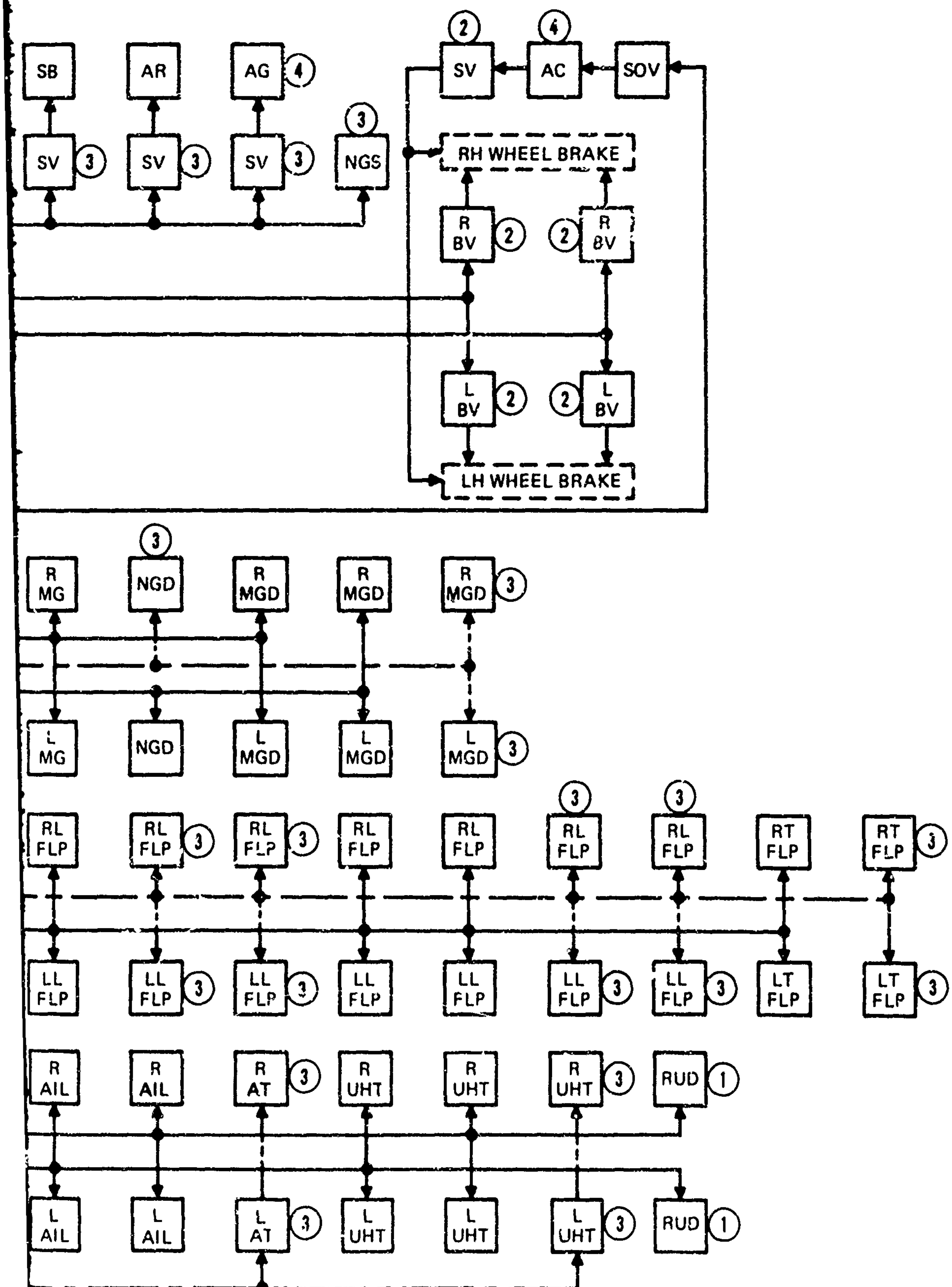

Figure 39. Concept No. 4 Electromechanical Backup Schematic Diagram

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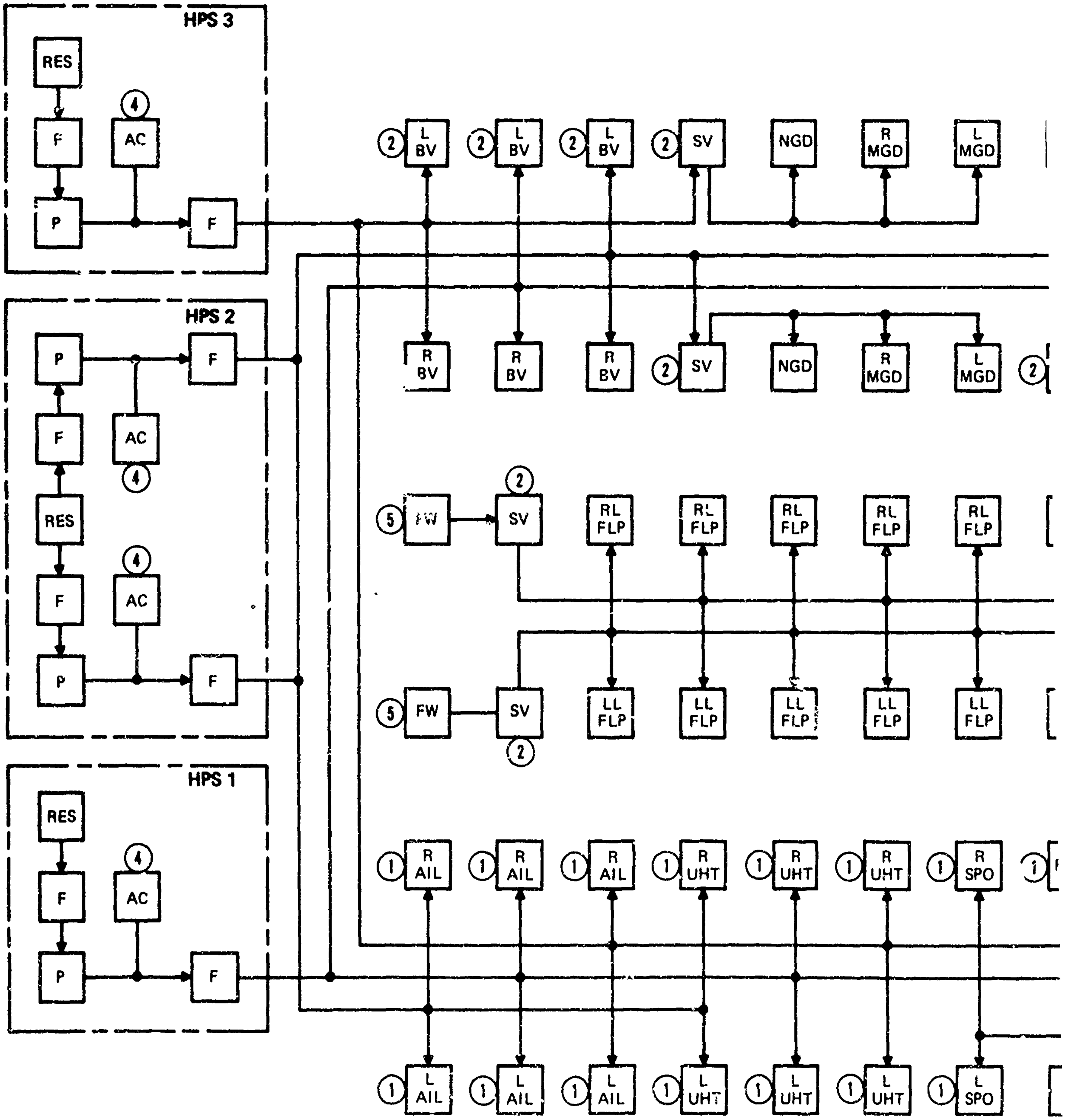

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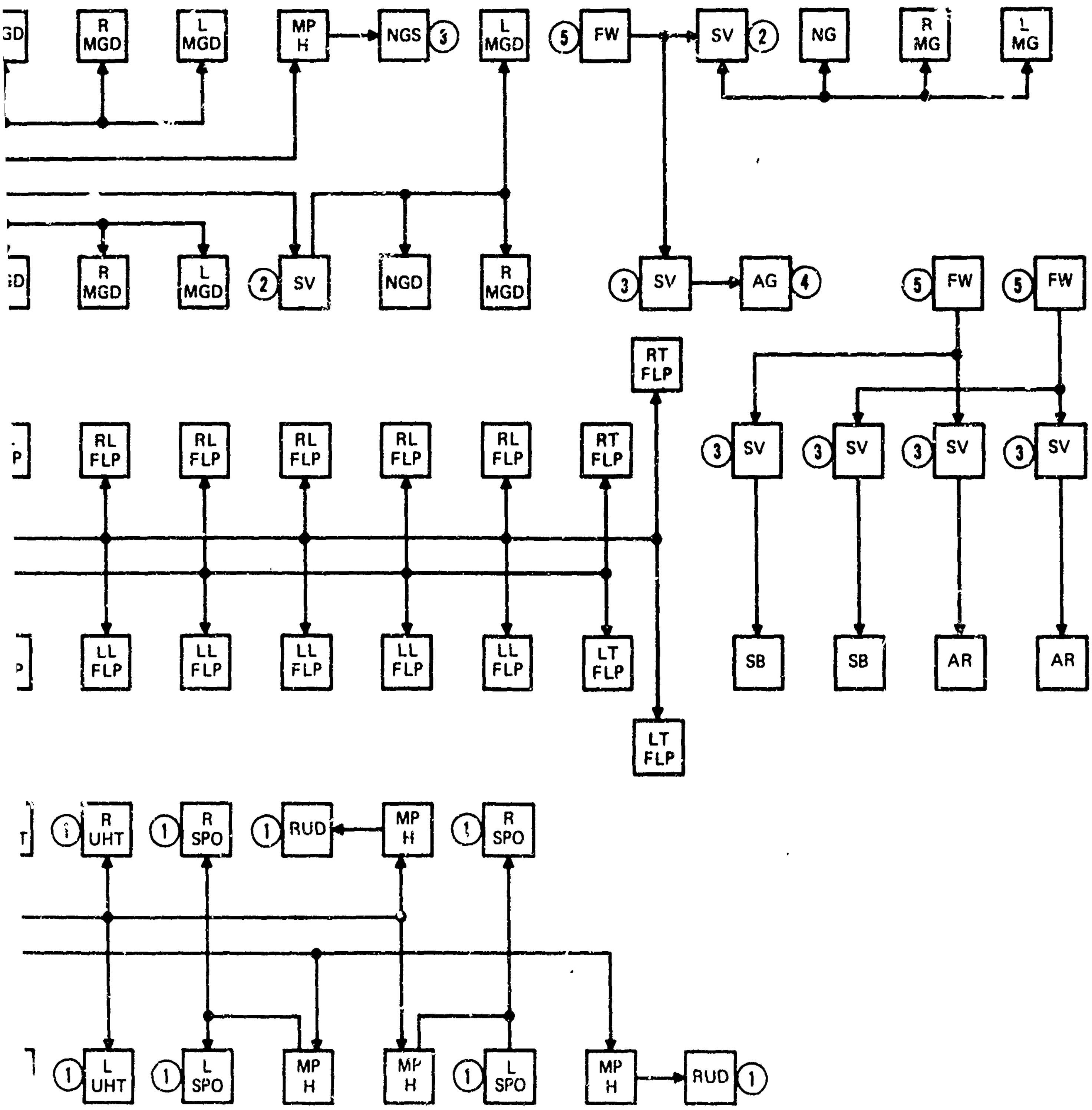

Figure 40. Concept No. 5 Flywheel Power Schematic Diagram

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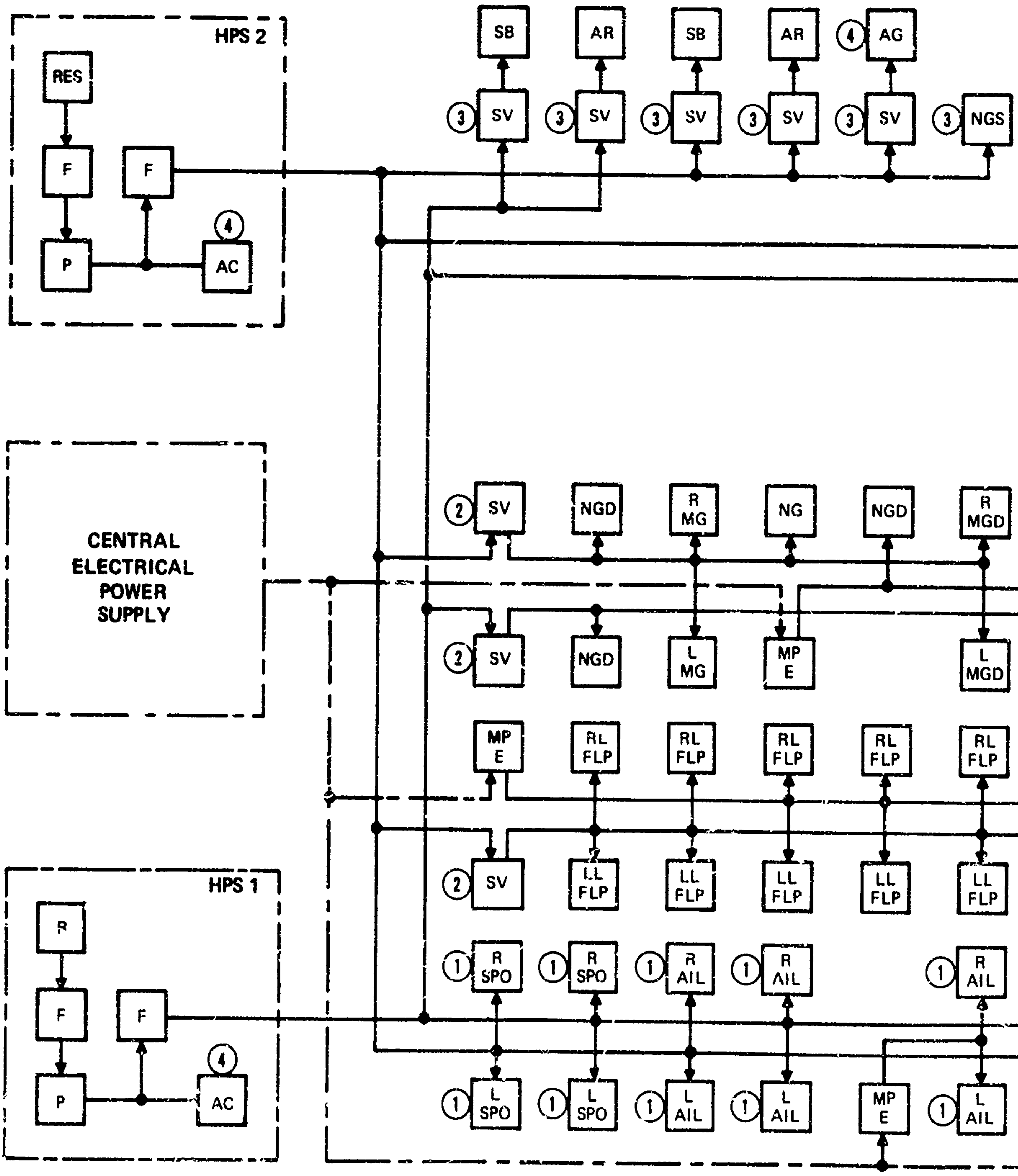

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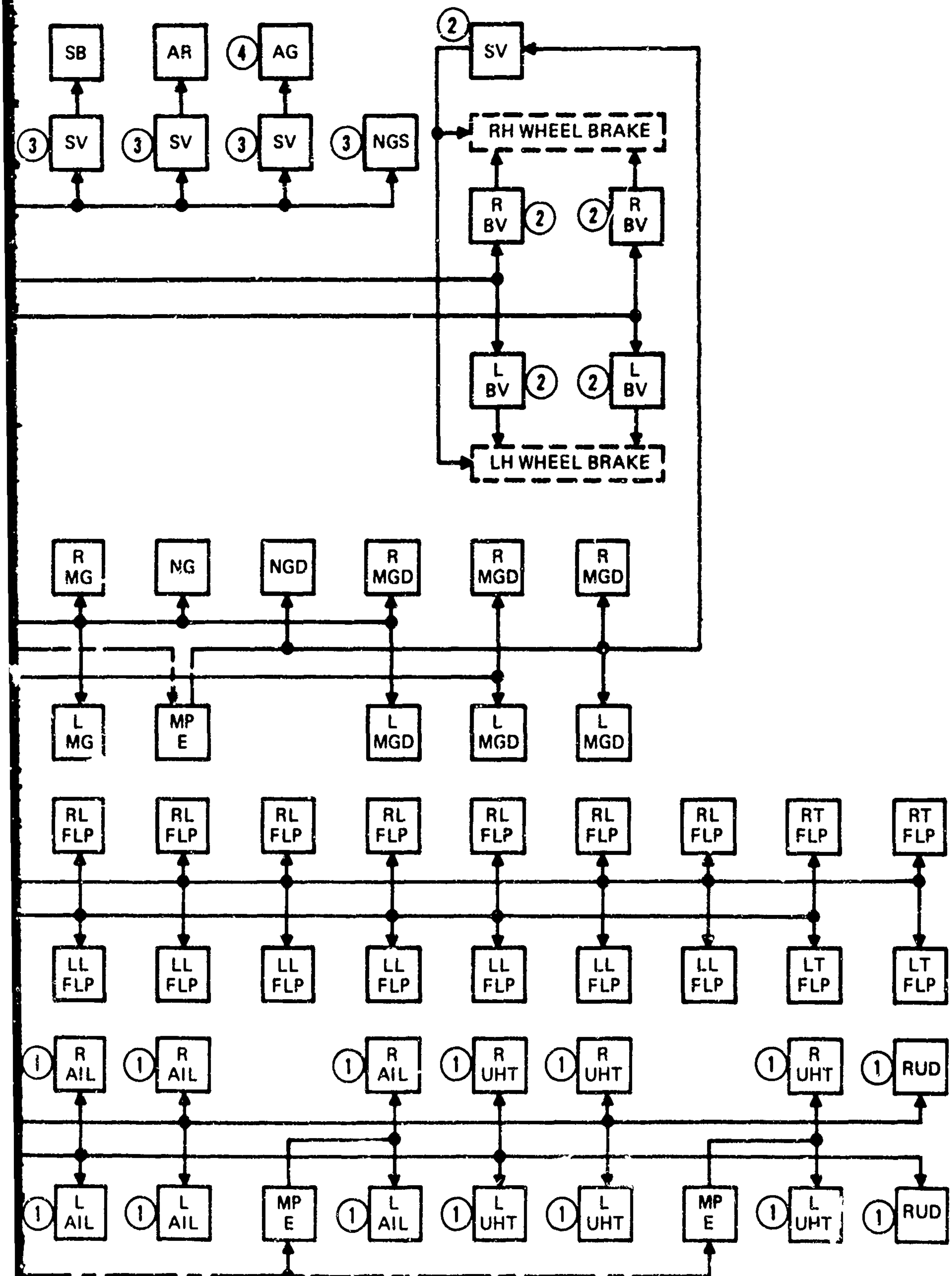

Figure 41. Concept No. 6 Electrohydraulic Backup Schematic Diagram

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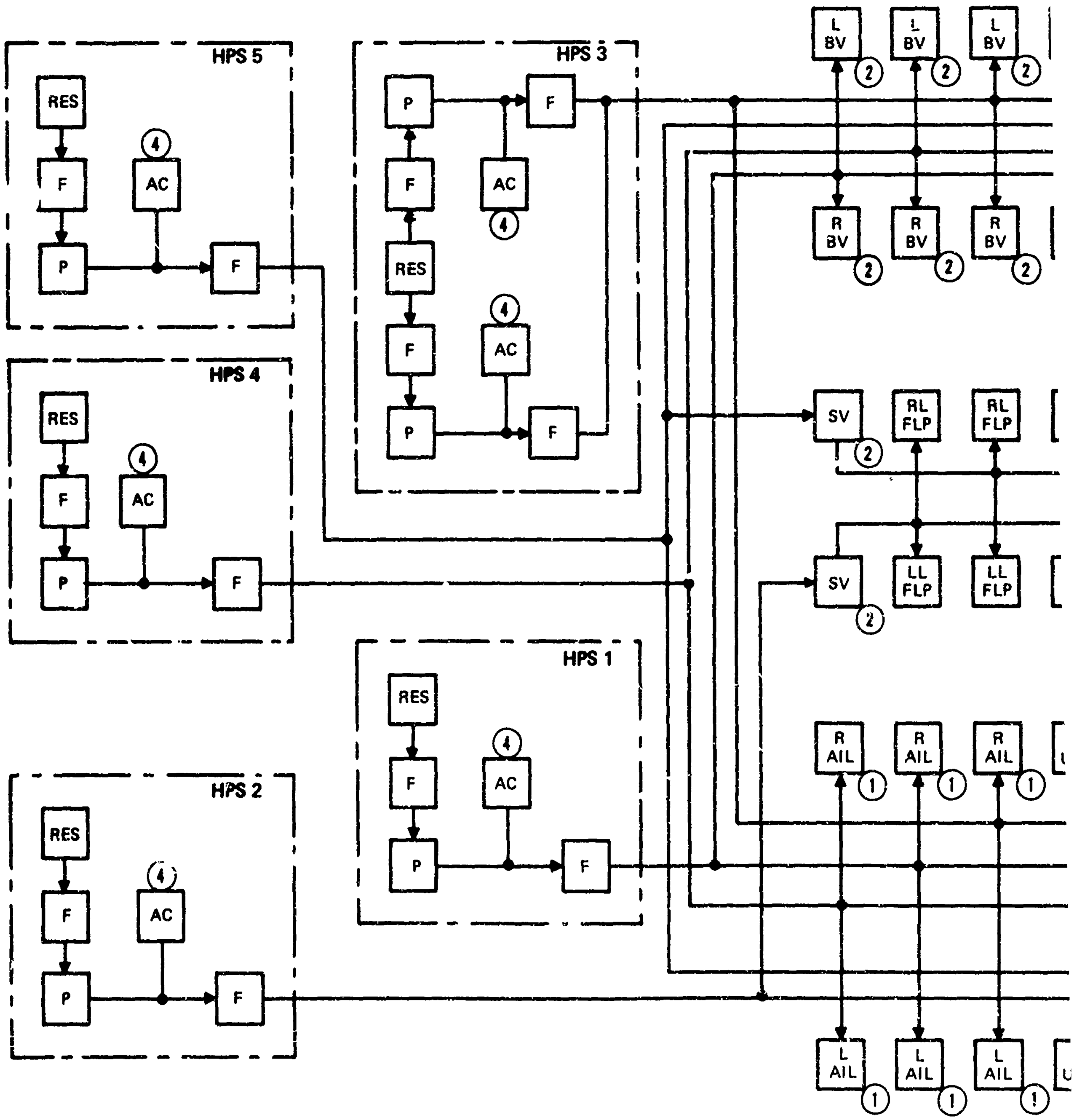

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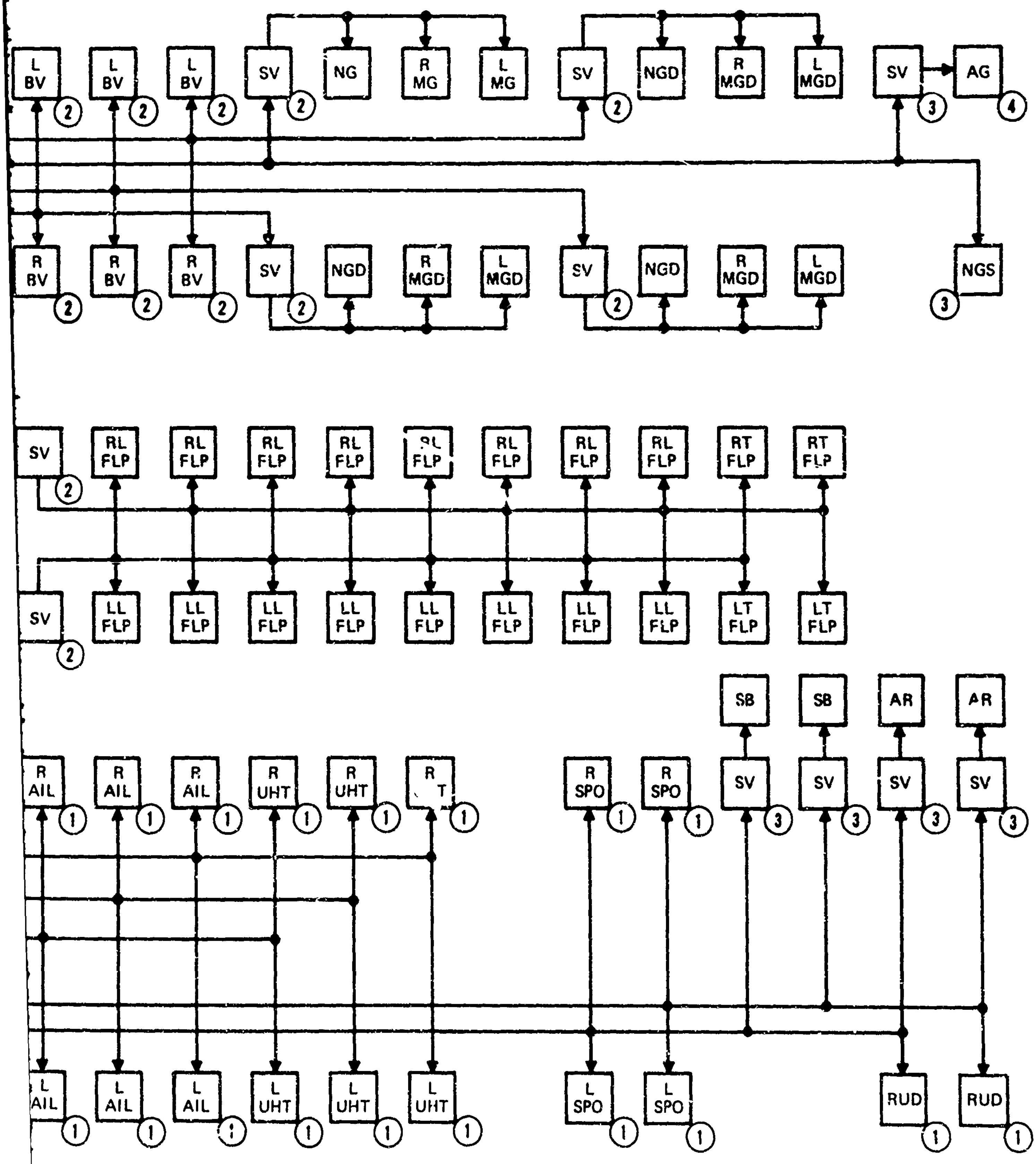

Figure 42 . Concept No. 7 Five Hydraulic Sources Schematic Diagram

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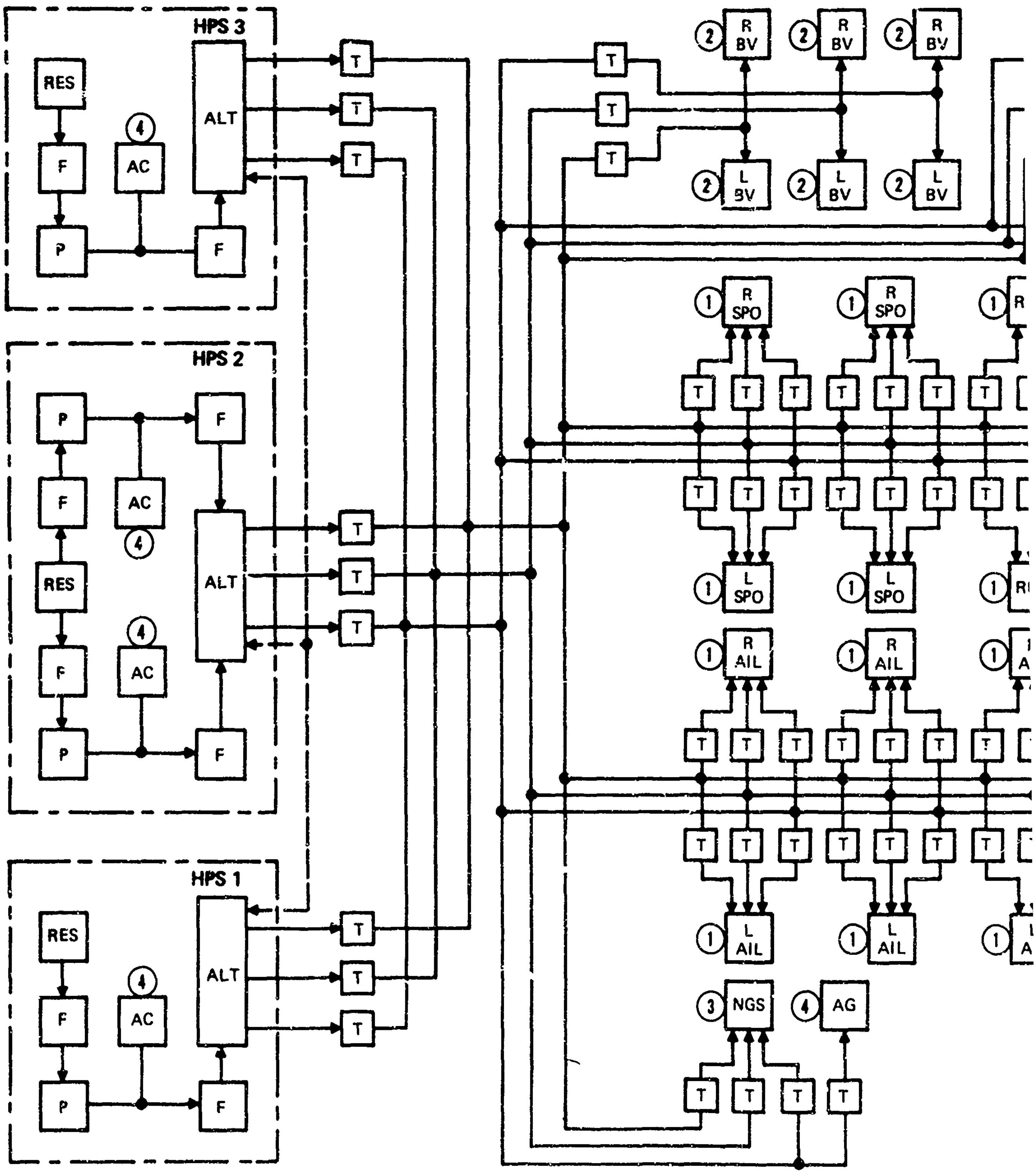

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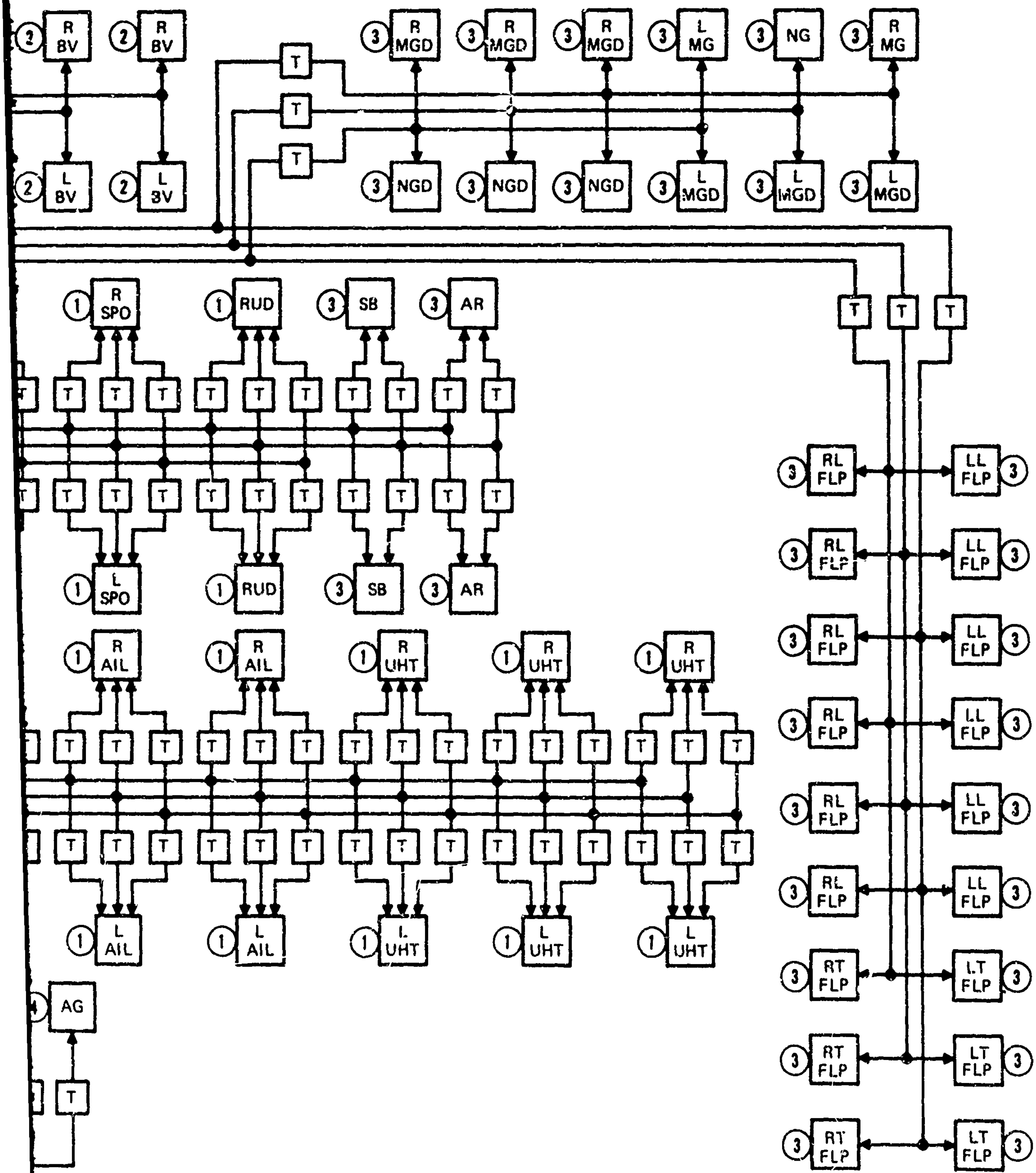

Figure 43. Concept No. 8 Pulsating Flow Schematic Diagram

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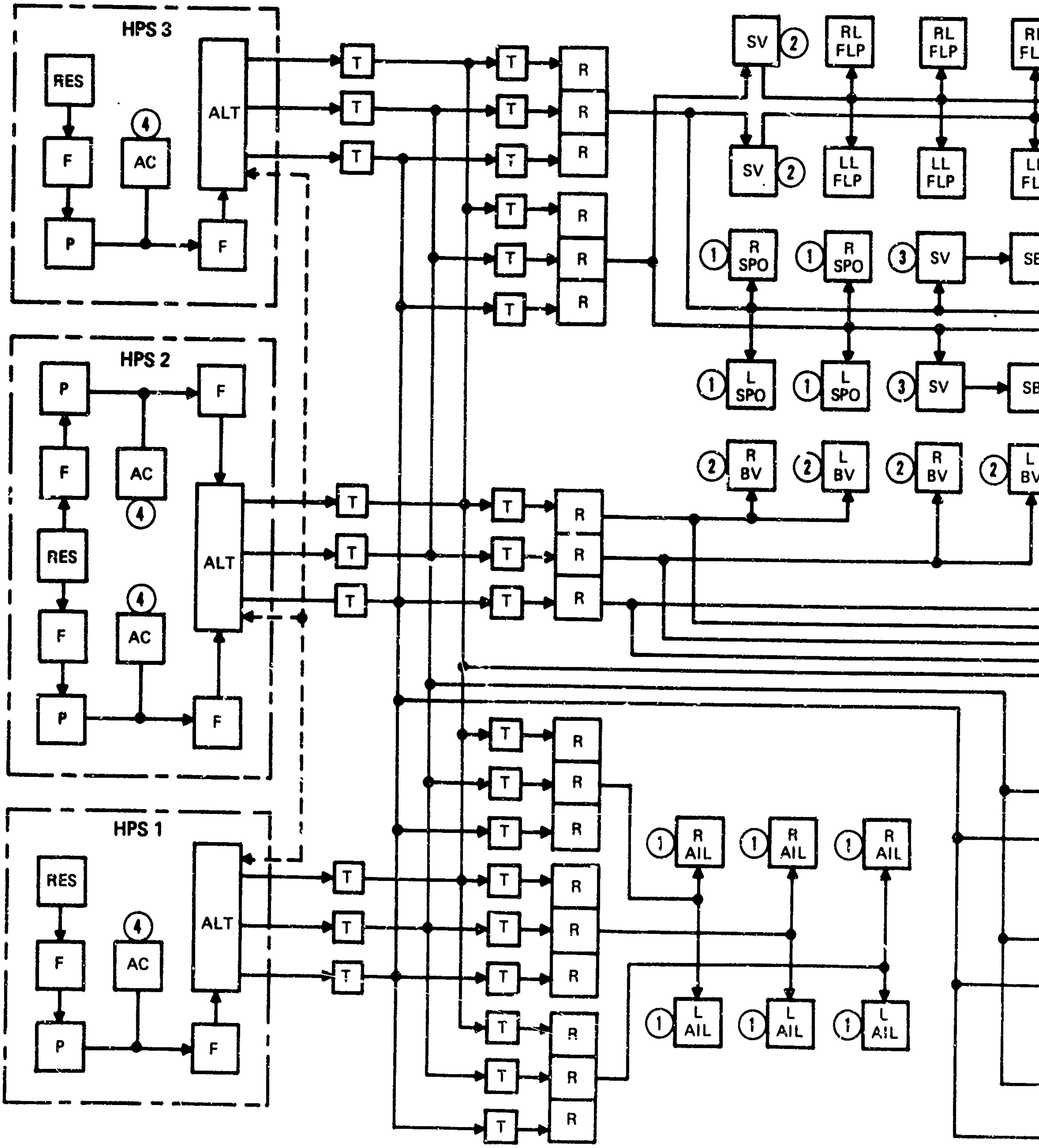

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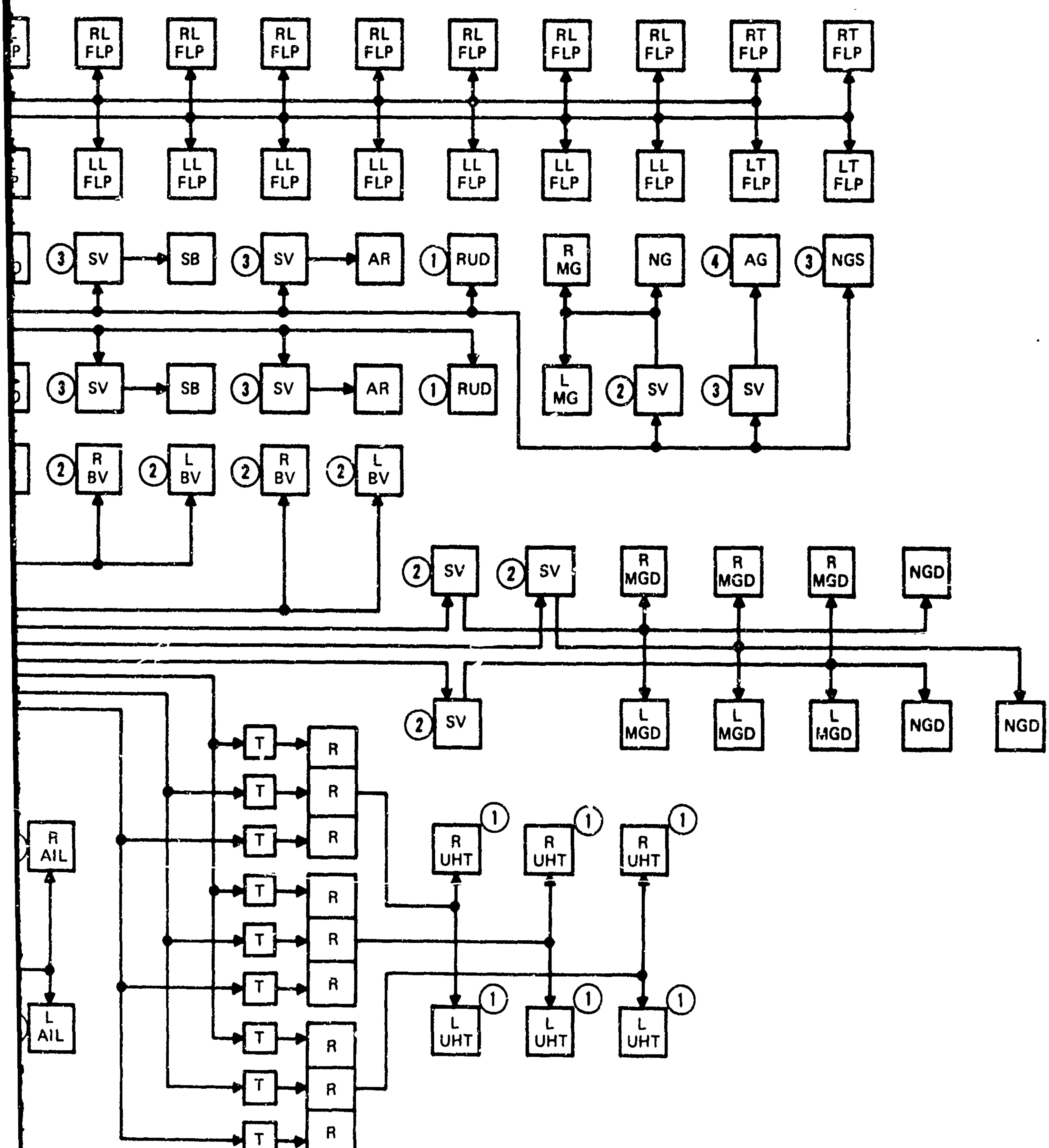

Figure 44. Concept No. 8A Pulsating Flow Schematic Diagram

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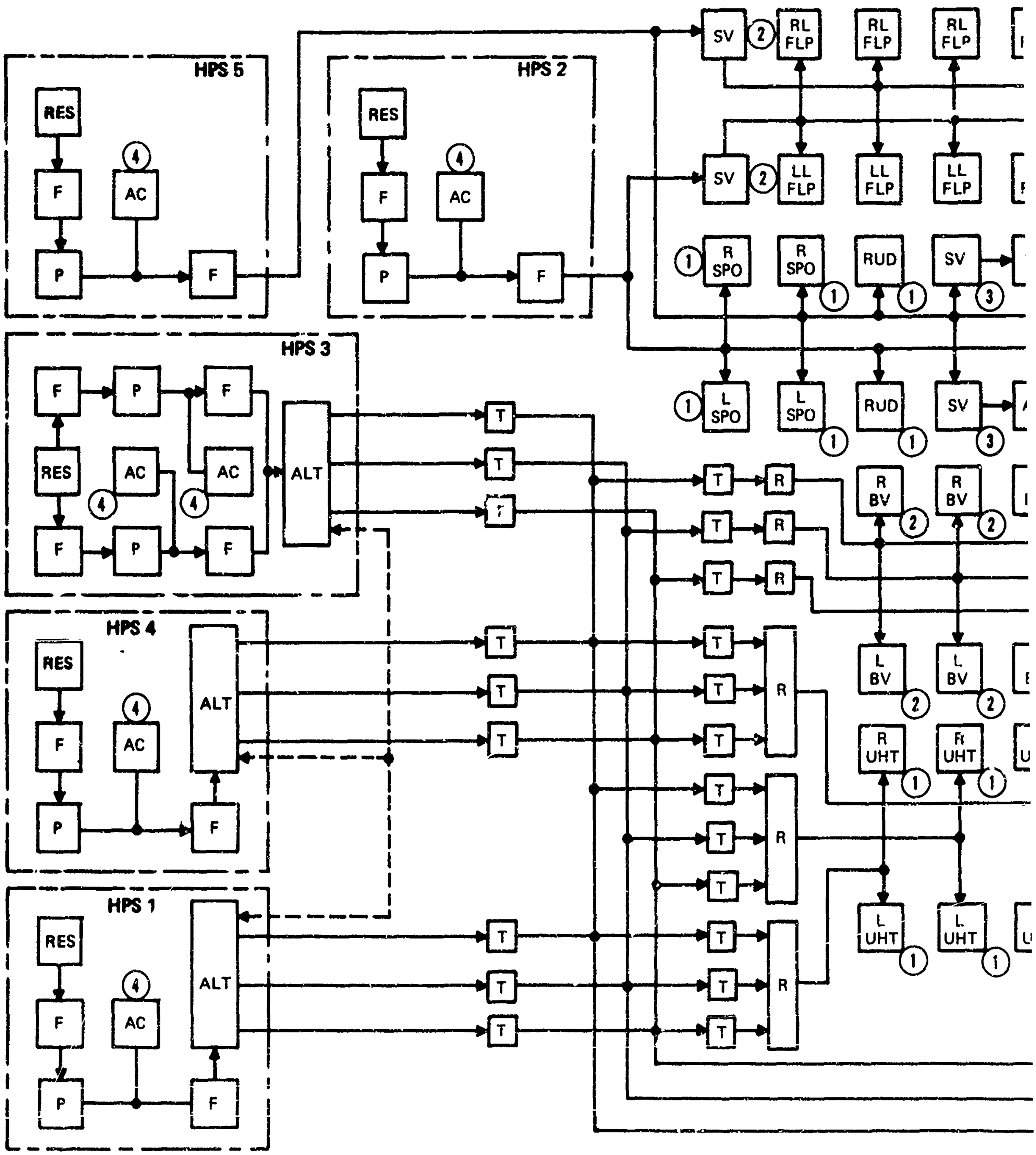
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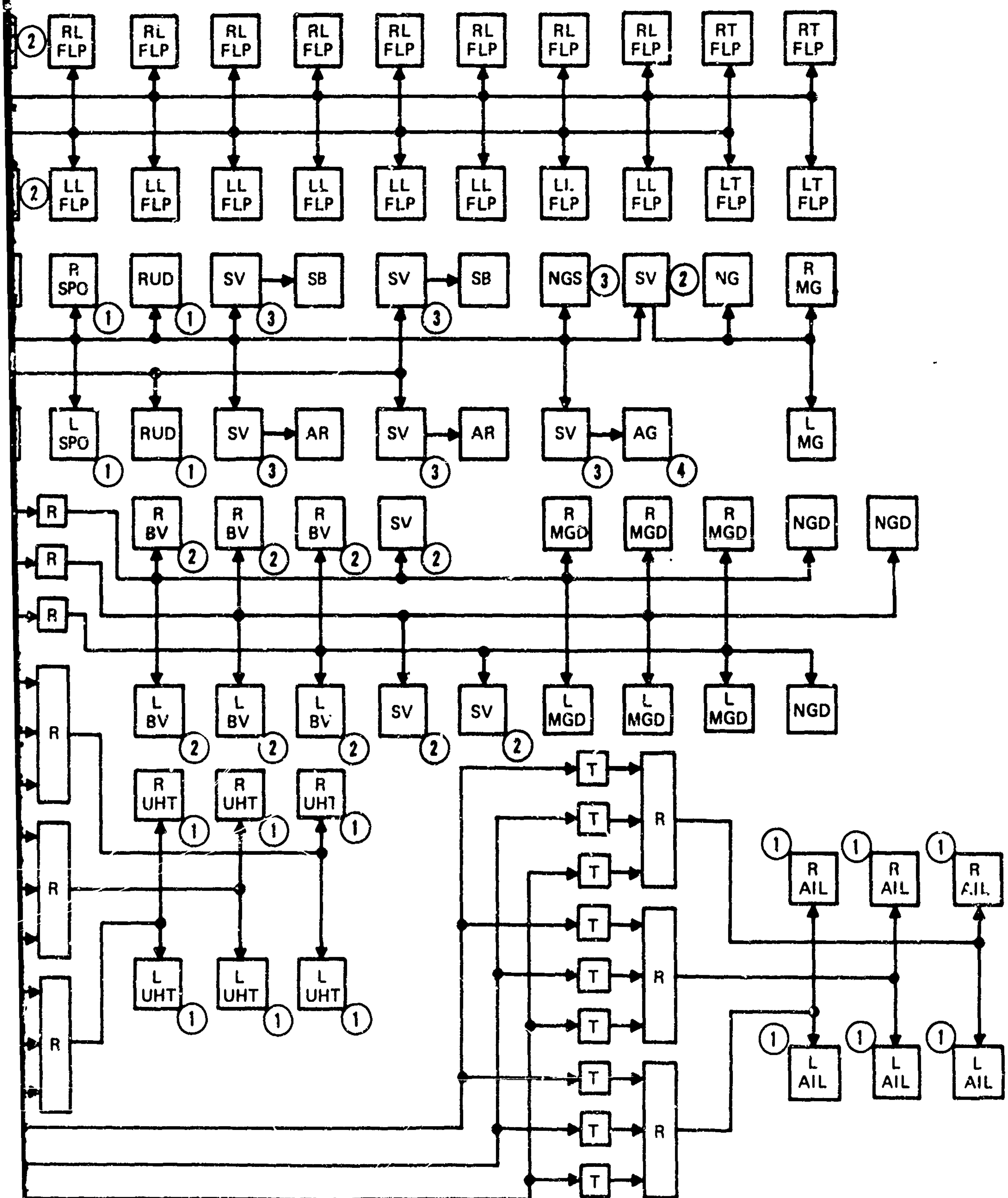

Figure 45. Concept No. 8B Pulsating Flow Schematic Diagram

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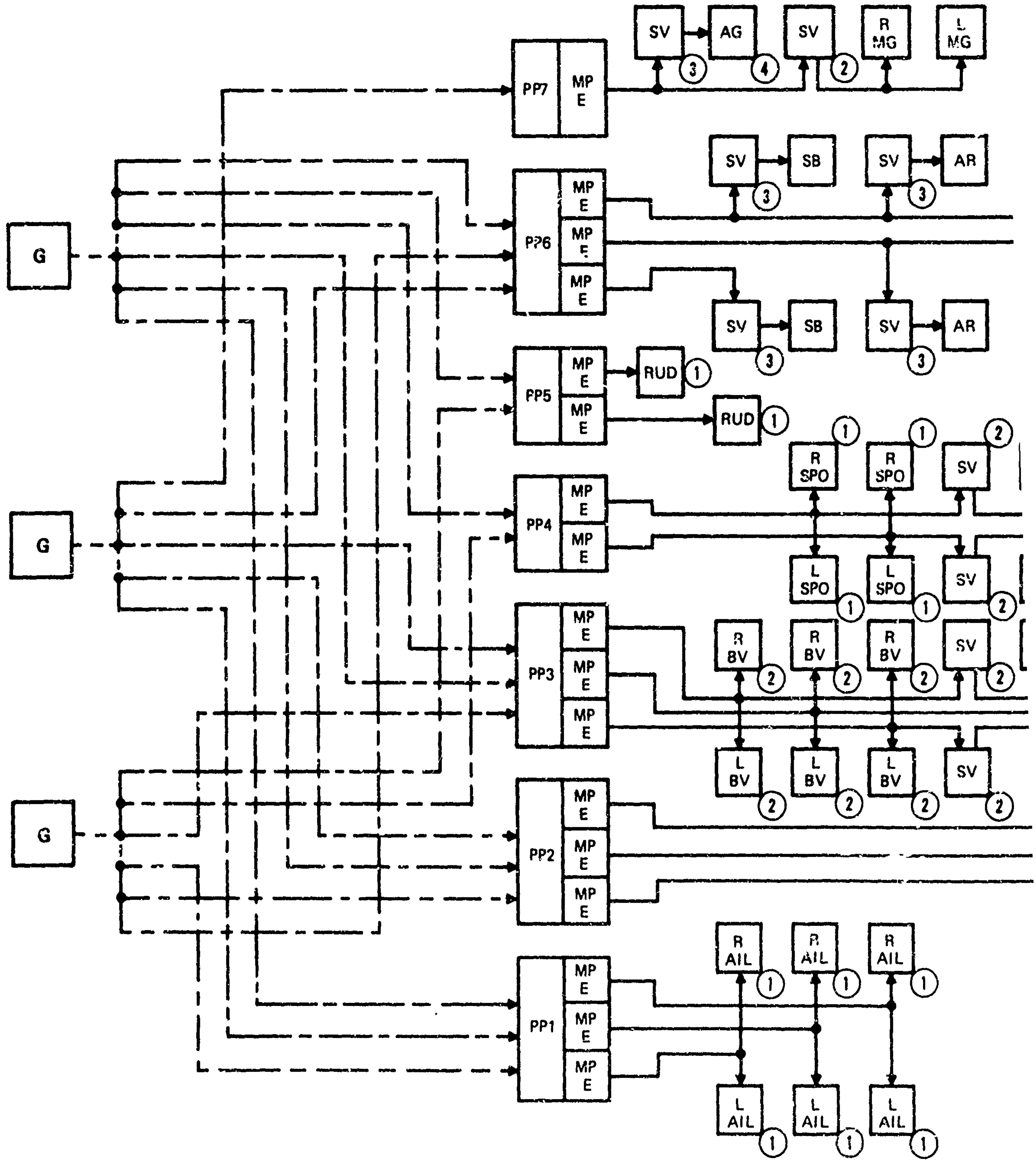

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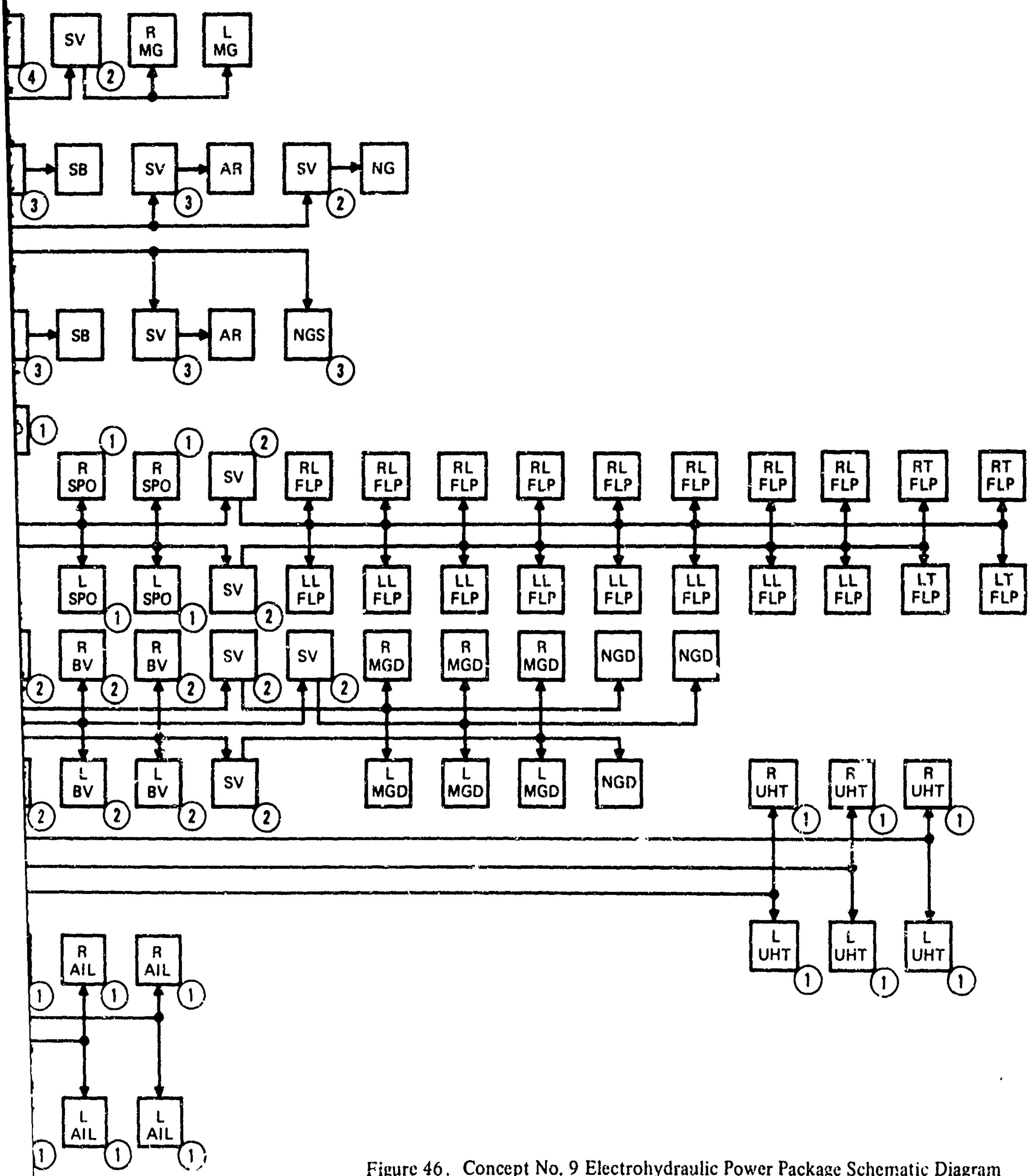

Figure 46. Concept No. 9 Electrohydraulic Power Package Schematic Diagram

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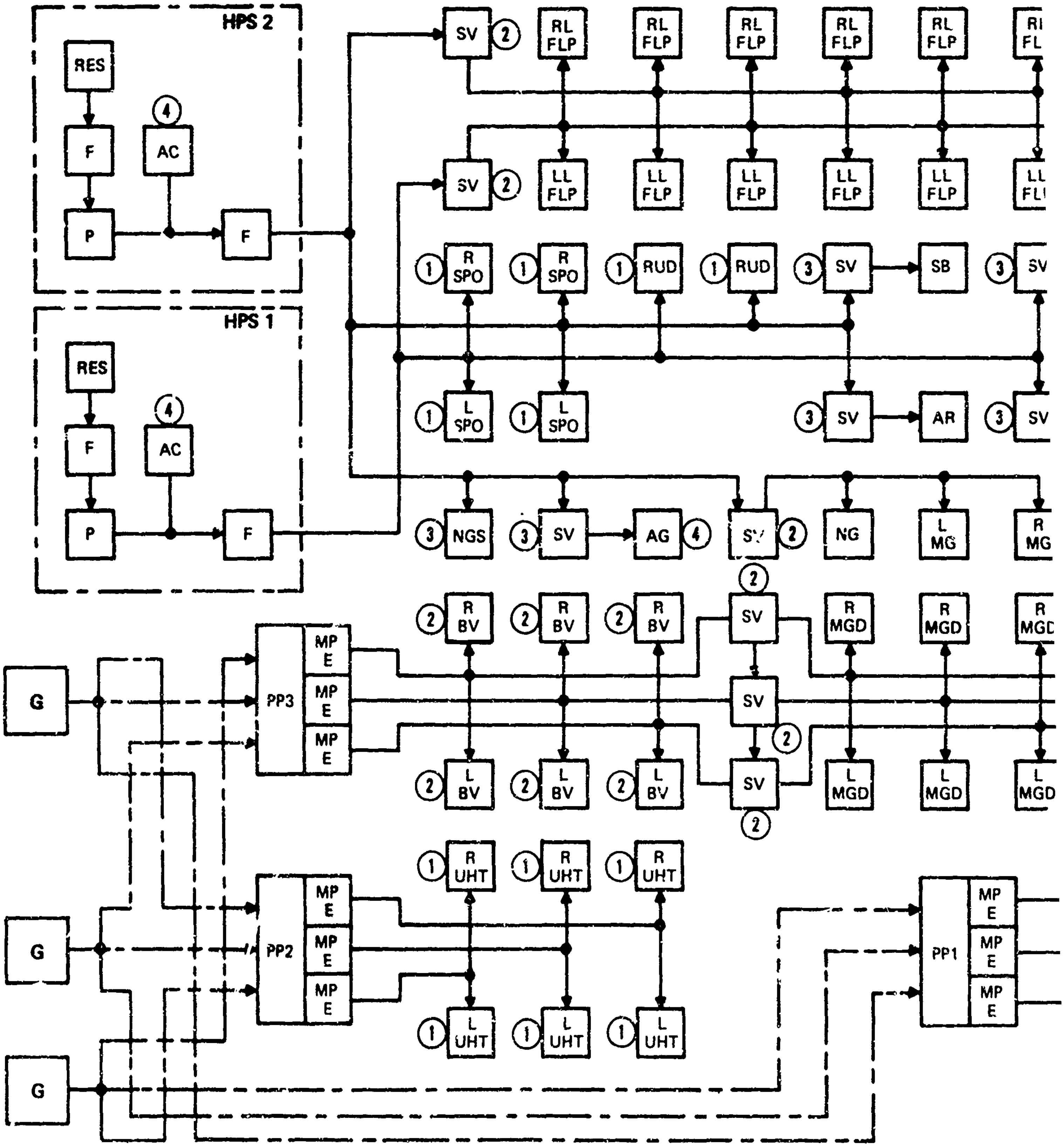

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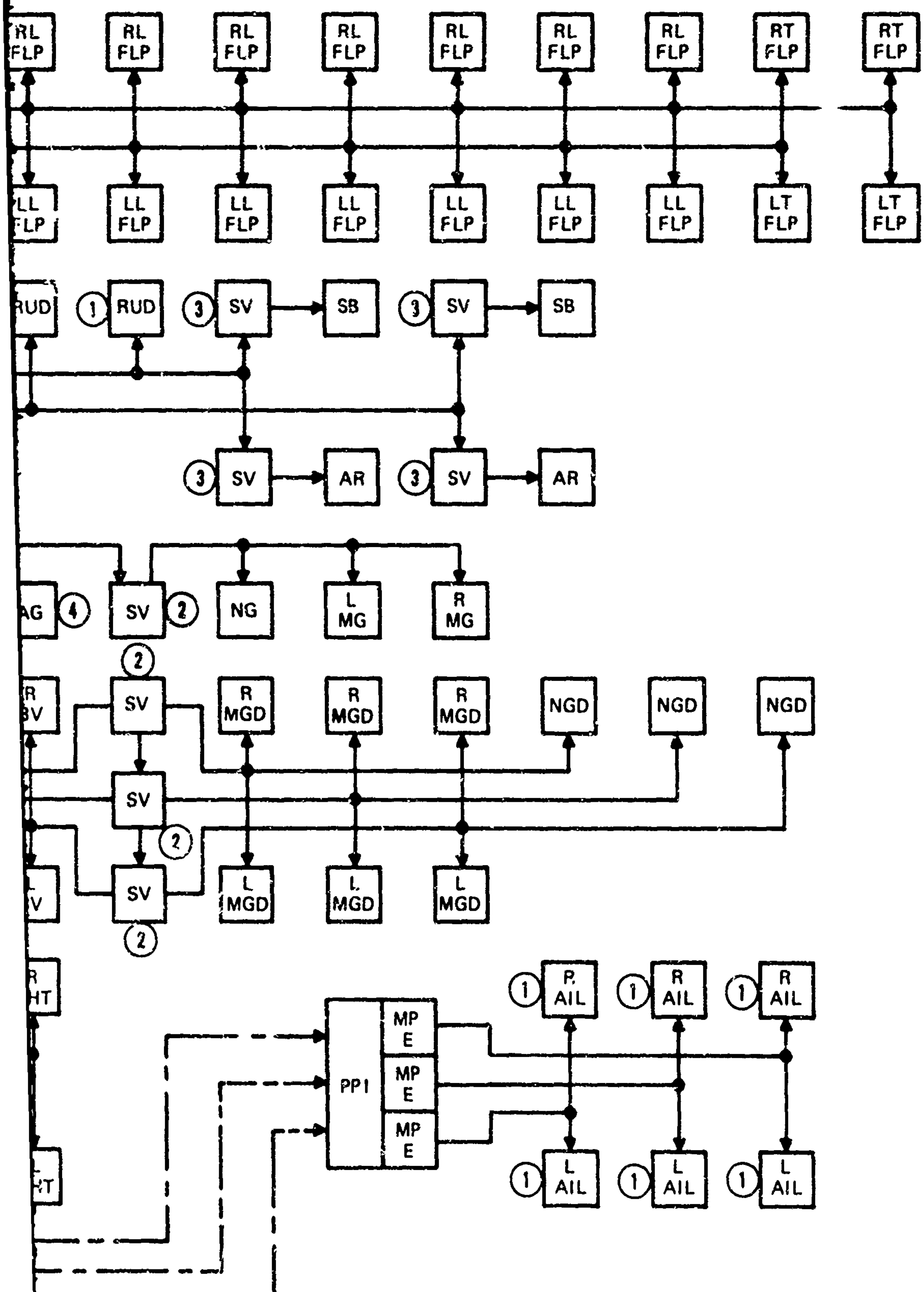

Figure 47. Concept No. 9A Electrohydraulic Power Package Schemati iagram

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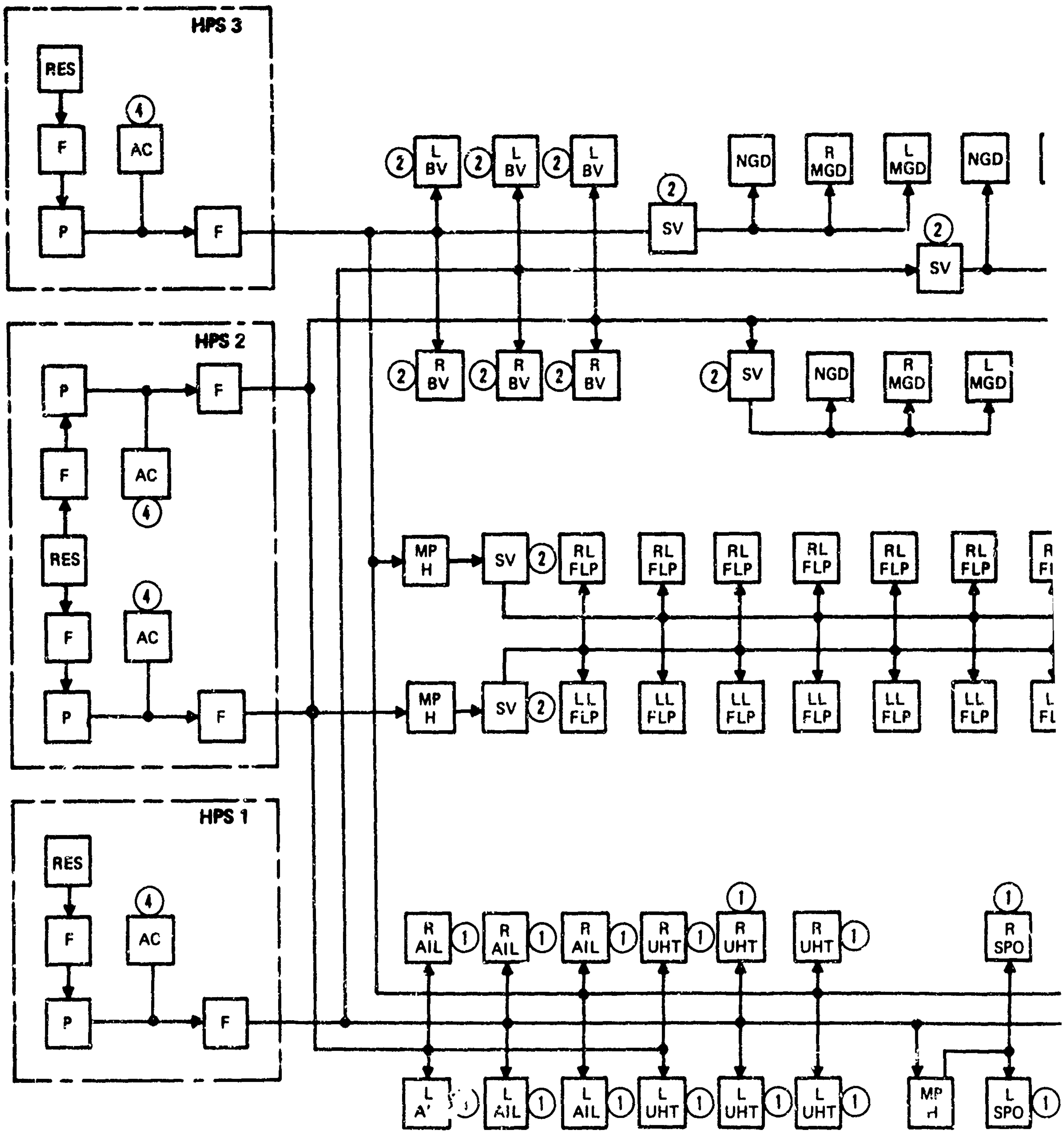

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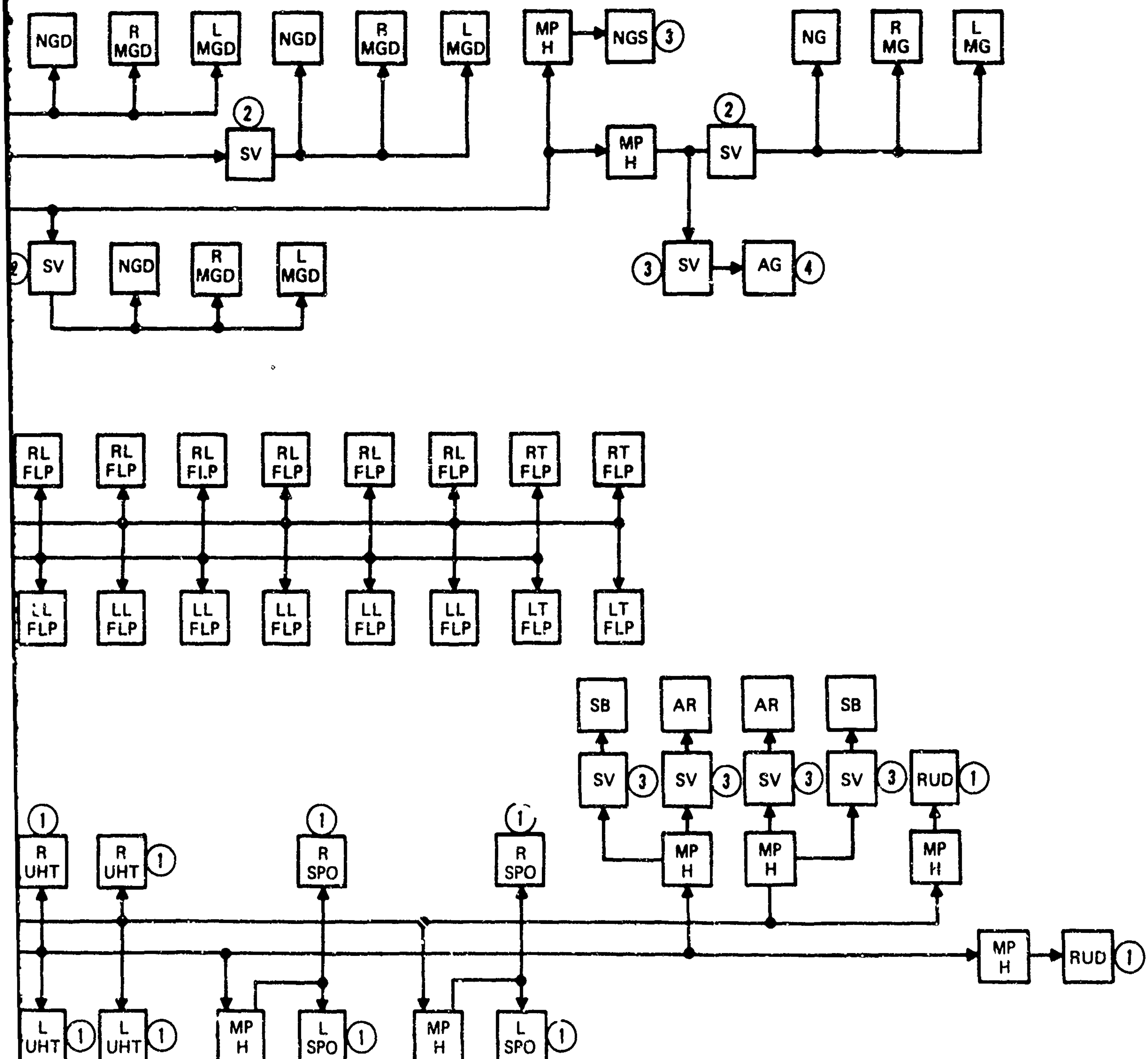

Figure 48. Concept No. 10 Motor Pump Isolation Schematic Diagram

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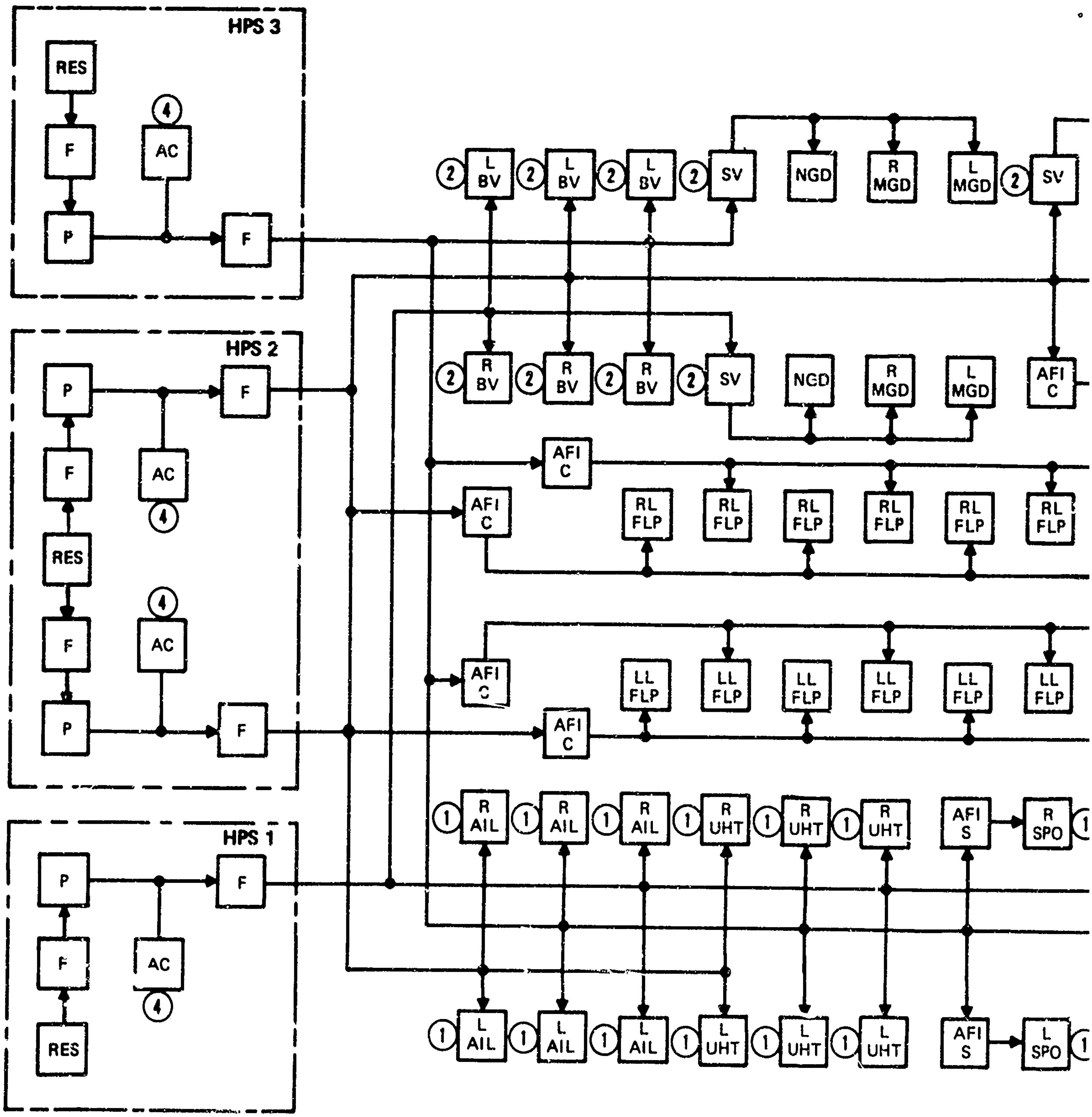

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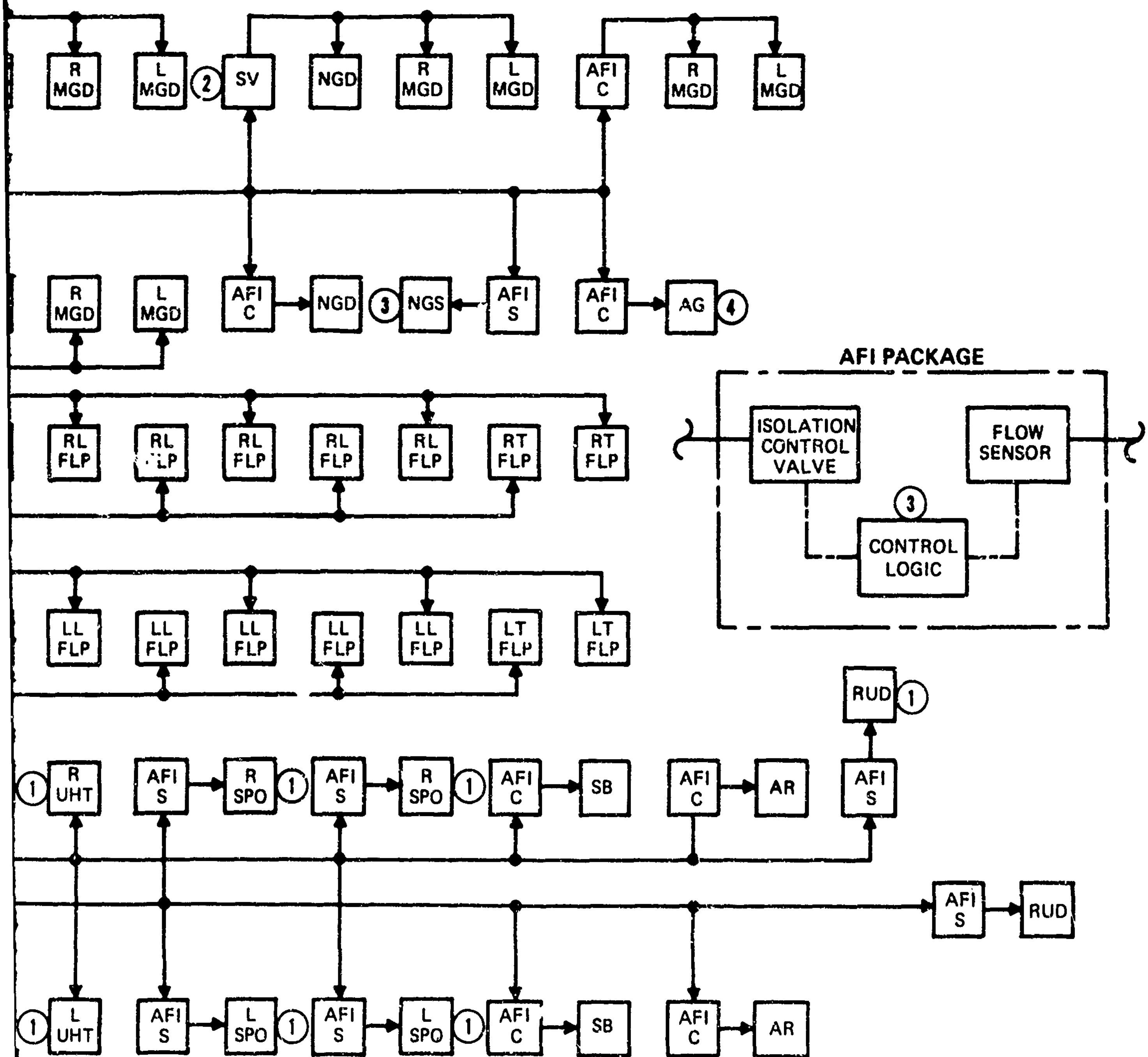

Figure 49. Concept No. 11 Automatic Failure Isolation Schematic Diagram

B.

Table XLII. Actuator List

NAME	TYPE	*CLASS	STROKE (IN.)	EFF PISTON AREA (SQ. IN.)	LOAD (POUNDS)	VOLUME (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
							1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
AILERON	HYDRAULIC TANDEM	C	5.3	9.9	29,600	297	4	-	-	-	-	-	-	-	-	-	-	-	-	-
	HYDRAULIC SINGLE	C	5.3	6.6	19,700	265	-	6	-	-	6	2	6	-	-	-	6	6	6	6
		C	5.3	6.6	19,700	331	-	-	-	-	-	-	-	6	6	6	-	-	-	-
		C	5.3	9.9	29,600	297	-	-	-	4	-	4	-	-	-	-	-	-	-	-
		C	5.3	2.2	19,700	120	-	-	6	-	-	-	-	-	-	-	-	-	-	-
AILERON TAB	ELECT-MECH	C	1.4	-	2,400	368	-	-	-	2	-	-	-	-	-	-	-	-	-	-
AIR REFUEL	HYDRAULIC SINGLE	C	8.0	0.3	1,000	99	1	2	-	2	-	2	-	-	-	-	-	-	-	-
		NC					-	-	-	-	2	-	2	-	-	-	2	2	2	2
		NC	8.0	0.3	1,000	120	-	-	-	-	-	-	-	2	2	2	-	-	-	-
		C	8.0	0.1	1,000	91	-	-	2	-	-	-	-	-	-	-	-	-	-	-
ARRESTING GEAR		C	18.0	1.4	4,000	204	1	1	-	1	-	1	-	-	-	-	-	-	-	-
		NC					-	-	-	-	1	-	1	-	-	-	1	1	1	1
		NC	18.0	1.4	4,000	217	-	-	-	-	-	-	-	1	1	1	-	-	-	-
		C	18.0	0.5	4,000	160	-	-	1	-	-	-	-	-	-	-	-	-	-	-
FLAP-L.E. INBOARD		C	1.6	3.8	11,400	121	4	8	-	4	-	4	-	-	-	-	-	-	-	-
		NC					-	-	-	-	8	4	8	-	8	8	8	8	8	8
		NC	1.6	3.8	11,400	137	-	-	-	-	-	-	-	6	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLII. Actuator List (Cont.)

NAME	TYPE	*CLASS	STROKE (IN.)	EFF PISTON AREA (SQ. IN.)	LOAD (POUNDS)	VOLUME (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
							1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
FLAP-L.E. INBOARD	HYDRAULIC SINGLE	C	1.6	1.3	11,400	77	-	-	8	-	-	-	-	-	-	-	-	-	-	-
	ELECT-MECH	NC	1.6	-	11,400	463	-	-	-	4	-	-	-	-	-	-	-	-	-	-
FLAP-L.E. OUTBOARD	HYDRAULIC SINGLE	C	5.5	1.4	4,100	106	4	8	-	4	-	4	-	-	-	-	-	-	-	-
		NC					-	-	-	-	8	4	8	-	8	8	8	8	8	8
		NC	5.5	1.4	4,100	129	-	-	-	-	-	-	-	6	-	-	-	-	-	-
		C	5.5	0.5	4,100	84	-	-	8	-	-	-	-	-	-	-	-	-	-	-
	ELECT-MECH	NC	5.5	-	4,100	496	-	-	-	4	-	-	-	-	-	-	-	-	-	-
FLAP-T.E.	HYDRAULIC SINGLE	C	2.0	2.2	6,600	91	2	4	-	2	-	2	-	-	-	-	-	-	-	-
		NC					-	-	-	-	4	2	4	-	4	4	4	4	4	4
		NC	2.0	2.2	6.600	106	-	-	-	-	-	-	-	6	-	-	-	-	-	-
		C	2.0	0.7	6,600	67	-	-	4	-	-	-	-	-	-	-	-	-	-	-
	ELECT-MECH	NC	2.0	-	6,600	385	-	-	-	2	-	-	-	-	-	-	-	-	-	-
MAIN GEAR	HYDRAULIC SINGLE	C	26.0	3.3	-	396	2	2	-	2	-	2	-	-	-	-	-	-	-	-
		NC					-	-	-	-	2	-	2	-	2	2	2	2	2	2
		NC	26.0	3.3	-	447	-	-	-	-	-	-	-	2	-	-	-	-	-	-
		C	26.0	1.1	-	246	-	-	2	-	-	-	-	-	-	-	-	-	-	-
MAIN GEAR DOOR		C	12.0	1.0	3,000	146	2	6	-	4	6	6	6	-	-	-	6	6	6	6

*C = CRITICAL NC = NONCRITICAL

Table XLII. Actuator List (Cont.)

NAME	TYPE	*CLASS	STROKE (IN.)	EFF PISTON AREA (SQ. IN.)	LOAD (POUNDS)	VOLUME (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
							1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
MAIN GEAR DOOR	HYDRAULIC SINGLE	C	12.0	1.0	3,000	169	-	-	-	-	-	-	-	6	6	6	-	-	-	-
		C	12.0	0.3	3,000	99	-	-	6	-	-	-	-	-	-	-	-	-	-	-
	ELECT-MECH	C	12.0	-	3,000	706	-	-	-	2	-	-	-	-	-	-	-	-	-	-
NOSE GEAR	HYDRAULIC SINGLE	C	20.0	2.9	8,800	307	1	1	-	1	-	1	-	-	-	-	-	-	-	-
		NC					-	-	-	-	1	-	1	-	1	1	1	1	1	1
		NC	20.0	2.9	8,800	371	-	-	-	-	-	-	-	1	-	-	-	-	-	-
		C	20.0	1.0	8,800	204	-	-	1	-	-	-	-	-	-	-	-	-	-	-
NOSE GEAR DOOR		C	12.0	0.8	2,400	135	1	3	-	2	3	3	3	-	-	-	3	3	3	3
		C	12.0	0.8	2,400	158	-	-	-	-	-	-	-	3	3	3	-	-	-	-
		C	12.0	0.3	2,400	99	-	-	3	-	-	-	-	-	-	-	-	-	-	-
	ELECT-MECH	C	12.0	-	2,400	706	-	-	-	1	-	-	-	-	-	-	-	-	-	-
NOSE GEAR STEERING	HYDRAULIC SINGLE	C	3.7	7.0	21,000	240	1	1	-	1	-	1	-	-	-	-	-	-	-	-
		NC					-	-	-	-	1	-	1	-	1	1	1	1	1	1
		NC	3.7	7.0	21,000	263	-	-	-	-	-	-	-	1	-	-	-	-	-	-
		C	3.7	1.5	21,000	92	-	-	1	-	-	-	-	-	-	-	-	-	-	-
RUDDER	HYDRAULIC TANDEM	C	3.3	3.5	10,500	96	2	-	-	-	-	-	-	-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLII. Actuator List (Cont.)

NAME	TYPE	*CLASS	STROKE (IN.)	EFF PISTON AREA (SQ. IN.)	LOAD (POUNDS)	VOLUME (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
							1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
RUDDER	HYDRAULIC SINGLE	C	3.3	3.5	10,500	132	-	2	-	2	-	2	-	-	-	-	-	-	-	-
		NC					-	-	-	-	2	-	2	-	2	2	2	2	2	2
		NC	3.3	3.5	10,500	163	-	-	-	-	-	-	-	2	-	-	-	-	-	-
		C	3.3	1.2	10,500	82	-	-	2	-	-	-	-	-	-	-	-	-	-	-
SPEED BRAKE		C	33.5	8.4	25,100	1021	1	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	33.5	4.2	12,500	540	-	2	-	2	-	2	-	-	-	-	-	-	-	-
		NC					-	-	-	-	2	-	2	-	2	2	2	2	2	2
		NC	33.5	4.2	12,500	630	-	-	-	-	-	-	-	2	-	-	-	-	-	-
		C	33.5	1.4	12,500	323	-	-	2	-	-	-	-	-	-	-	-	-	-	-
SPOILER	HYDRAULIC TANDEM	C	2.1	3.6	10,900	87	4	-	-	-	-	-	-	-	-	-	-	-	-	-
	HYDRAULIC SINGLE	C	2.1	3.6	10,900	92	-	4	-	4	-	4	-	-	-	-	-	-	-	-
		NC					-	-	-	-	4	-	4	-	4	4	4	4	4	4
		NC	2.1	3.6	10,900	118	-	-	-	-	-	-	-	4	-	-	-	-	-	-
		C	2.1	1.2	10,900	74	-	-	4	-	-	-	-	-	-	-	-	-	-	-
UHT	HYDRAULIC TANDEM	C	8.2	9.7	29,000	381	4	-	-	-	-	-		-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLII. Actuator List (Cont.)

NAME	TYPE	*CLASS	STROKE (IN.)	EFF PISTON AREA (SQ. IN.)	LOAD (POUNDS)	VOLUME (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
							1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
UHT	HYDRAULIC SINGLE	C	8.2	6.5	19,300	310	-	6	-	-	6	2	6	-	-	-	6	6	6	6
		C	8.2	6.5	19,300	360	-	-	-	-	-	-	-	6	6	6	-	-	-	-
		C	8.2	2.2	19,300	147	-	-	6	-	-	-	-	-	-	-	-	-	-	-
		C	8.2	9.7	19,300	381	-	-	-	4	-	4	-	-	-	-	-	-	-	-
	ELECT-MECH	C	1.1	-	9,700	576	-	-	-	2	-	-	-	-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
ACCUMULATOR	C	-	30	-	44	4	4	4	2	4	2	4	4	4	2	-	-	4	4
	NC					-	-	-	-	-	-	2	-	-	4	-	2	-	-
	C	-	50	-	76	1	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	-	100	-	148	2	-	-	1	-	-	-	-	-	-	-	-	-	-
ALTERNATOR HYDRAULIC	C	30	33	AREA RATIO = 1:1	395	-	-	-	-	-	-	-	3	3	3	-	-	-	-
AFI-SHUT-OFF VALVE	C	10.5	-	AREA RATIO = 1:1	155	-	-	-	-	-	-	-	-	-	-	-	-	-	6
	C	3.5	-	AREA RATIO = 1:1	30	-	-	-	-	-	-	-	-	-	-	-	-	-	1
AFI-SEL VALVE	C	29.0	-	AREA RATIO = 1:1	180	-	-	-	-	-	-	-	-	-	-	-	-	-	2
	C	3.5	-	AREA RATIO = 1:1	30	-	-	-	-	-	-	-	-	-	-	-	-	-	7
	C	1.2	-	AREA RATIO = 1:1	14	-	-	-	-	-	-	-	-	-	-	-	-	-	2
BRAKE VALVE	C	-	-	3000 PSI BOOST	24	2	6	-	4	6	4	6	6	6	6	6	6	6	6
	C	-	-	9000 PSI BOOST	24	-	-	6	-	-	-	-	-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A'	10	11
FILTER	C	9.4	-	-	71	2	-	-	-	-	-	-	-	-	-	-	-	-	-
					48	-	-	4	-	-	-	-	-	-	-	-	-	-	-
	C	18.2	-	-	116	-	-	4	-	-	-	-	-	-	-	-	-	-	-
	C	29.0	-	-	116	-	4	-	-	4	-	-	-	-	-	-	-	4	4
	NC	36.4	-	-	116	-	-	-	-	-	-	4	-	-	-	-	-	-	-
	NC	40.0	-	-	150	-	-	-	-	-	-	-	-	-	4	-	4	-	-
	C	40.0	-	-	150	4	-	-	-	-	-	8	-	-	-	-	-	-	-
	C	48.0	-	-	150	-	-	-	-	-	-	-	8	8	8	-	-	-	-
	C	54.6	-	-	150	-	4	-	-	4	-	-	-	-	-	-	-	4	4
	C	63.0	-	-	150	2	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	66.7	-	-	150	-	-	-	4	-	4	-	-	-	-	-	-	-	-
FLYWHEEL PACKAGE:	NC	-	-	-	245	-	-	-	-	2	-	-	-	-	-	-	-	-	-
(1) MOTOR	-	28 SCFM @ 90 PSIA	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
(2) PUMP V.D.	-	21	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(3) RESERVOIR	-	-	40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(4) FLYWHEEL	-	-	-	11,000 RPM 12 IN. DIA. 12 LB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FLYWHEEL PACKAGE	NC	-	-	-	105	-	-	-	-	2	-	-	-	-	-	-	-	-	-
(1) MOTOR	-	38 SCFM @ 90 PSIA	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(2) PUMP V.D.	-	7	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(3) RESERVOIR	-	-	60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(4) FLYWHEEL	-	-	-	11,000 RPM 12 IN. DIA. 20 LB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FLYWHEEL PACKAGE:	NC	-	-	-	245	-	-	-	-	1	-	-	-	-	-	-	-	-	-
(1) MOTOR	-	28 SCFM @ 90 PSI	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(2) PUMP V.D.	-	10	-	11,000 RPM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(3) RESERVOIR	-	-	35	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
(4) FLYWHEEL	-	-	-	11,000 RPM 12 IN. DIA. 10 LB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GENERATOR	C	-	-	12,000 RPM 90 KVA	1420	-	-	-	-	-	-	-	-	-	-	2	2	-	-
	C	-	-	12,000 RPM 50 KVA	767	-	-	-	-	-	-	-	-	-	-	1	1	-	-
MOTORPUMP ELECTRIC	NC	1.1	7.0	11,300 RPM 3 HP IN PF PUMP	230	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	C	5.0	10.4	12,000 RPM 14 HP IN PV PUMP	300	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	C	5.0	12.0	12,000 RPM 14 HP IN PV PUMP	300	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	C	1.4	12.3	11,300 RPM 3 HP IN PF PUMP	250	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	C	22.1	14.1	12,000 RPM 40 KVA PV PUMP	1150	-	-	-	-	-	-	-	-	-	-	3	3	-	-
	C	18.2	13.5	12,000 RPM 30 KVA PV PUMP	1010	-	-	-	-	-	-	-	-	-	-	3	3	-	-
	C	3.3	8.0	11,600 RPM 6 KVA PV PUMP	241	-	-	-	-	-	-	-	-	-	-	3	3	-	-
	NC	22.0	18.8	12,000 RPM 40 KVA PF PUMP	1150	-	-	-	-	-	-	-	-	-	-	2	-	-	-
	NC	7.6	1.3	11,400 RPM 14 KVA PV PUMP	670	-	-	-	-	-	-	-	-	-	-	2	-	-	-
	NC	4.4	4.0	11,500 RPM 10 KVA PF PUMP	271	-	-	-	-	-	-	-	-	-	-	1	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
MOTORPUMP ELECTRIC	NC	21.0	-	12,000 RPM 40 KVA PF PUMP	1150	-	-	-	-	-	-	-	-	-	-	2	-	-	-
↓	NC	3.2	24.0	11,600 RPM 55 KVA PF PUMP	241	-	-	-	-	-	-	-	-	-	-	1	-	-	-
MOTORPUMP HYDRAULIC	C	24.6	30.0	3750 RPM PV PUMP	1200	-	-	-	-	2	-	-	-	-	-	-	-	2	-
	C	8.5	20.0	3280 RPM PV PUMP	560	-	-	-	-	2	-	-	-	-	-	-	-	2	-
	C	4.8	10.0	3000 RPM	395	-	-	-	-	1	-	-	-	-	-	-	-	1	-
	C	7.8	60.0	3000 RPM PV PUMP	207	-	-	-	-	-	-	-	-	-	-	-	-	2	-
	C	6.9	35.0	2650 RPM PV PUMP	183	-	-	-	-	-	-	-	-	-	-	-	-	1	-
↓	C	21.0	40.0	3200 RPM PV PUMP	590	-	-	-	-	-	-	-	-	-	-	-	-	2	-
PUMP	C	9.4	-	PV TYPE	343	1	-	-	-	-	-	-	-	-	-	-	-	-	-
					455	-	-	2	-	-	-	-	-	-	-	-	-	-	-
↓	C	18.2	-	PV TYPE	650	-	-	2	-	-	-	-	-	-	-	-	-	-	-

*C - CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
PUMP	C	28.2	-	PV TYPE	457	-	2	-	-	2	-	-	-	-	-	-	-	2	2
	NC	30.4	-	PV TYPE	457	-	-	-	-	-	-	2	-	-	2	-	2	-	-
	C	40.0	-	-	530	2	-	-	-	-	-	4	-	-	-	-	-	-	-
			-	PV TYPE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	48.0	-	PV TYPE	609	-	-	-	-	-	-	-	4	4	4	-	-	-	-
	C	54.6	-	PV TYPE	650	-	2	-	-	2	-	-	-	-	-	-	-	2	2
	C	63	-	PV TYPE	700	1	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	66.7	-	PV TYPE	700	-	-	-	2	-	2	-	-	-	-	-	-	-	-
RECTIFIER HYDRAULIC	C	14.6	7.0	3 PHASE	132	-	-	-	-	-	-	-	-	3	3	-	-	-	-
	C	12.0	10.8	3 PHASE	100	-	-	-	-	-	-	-	-	3	3	-	-	-	-
	C	9.0	4.3	SINGLE PHASE	75	-	-	-	-	-	-	-	-	3	3	-	-	-	-
	NC	40.4	11.0	3 PHASE	200	-	-	-	-	-	-	-	-	2	-	-	-	-	-

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Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
RESERVOIR	C	-	30	-	49	-	-	-	-	-	-	-	3	3	3	-	-	-	-
	C	-	170	-	382	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	C	-	205	-	425	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	C	-	255	-	495	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	C	-	280	-	420	-	-	-	-	3	-	-	-	-	-	-	-	3	-
	C	-	320	-	460	-	-	-	-	-	-	3	-	-	-	-	-	-	-
	NC	-	350	-	495	-	-	-	-	-	-	1	-	-	1	-	1	-	-
	C	-	410	-	703	1	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	-	562	-	890	-	1	-	-	-	-	-	-	-	-	-	-	-	1
	C	-	610	-	967	1	1	-	-	-	-	-	-	-	-	-	-	-	1
	C	-	759	-	1180	-	-	-	1	-	1	-	-	-	-	-	-	-	-
	C	-	782	-	1200	-	1	-	-	-	-	-	-	-	-	-	-	-	1

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
RESERVOIR	C	-	789	-	1361	-	-	-	1	-	1	-	-	-	-	-	-	-	-
	NC	-	820	-	1300	-	-	-	-	-	-	1	-	-	1	-	1	-	-
	C	-	890	-	1342	1	-	-	-	-	-	-	-	-	-	-	-	-	-
SELECTOR VALVE-ELEC.	C	1.2	-	4 WAY 3 POS	14	1	2	2	2	-	2	-	-	-	-	-	-	-	-
	NC					-	-	-	-	2	-	2	-	2	2	2	2	2	-
	C	7.0	-	4 WAY 3 POS	54	-	-	2	-	-	-	-	-	-	-	-	-	-	-
	C	21.0	-	4 WAY 3 POS	79	-	2	-	2	-	2	-	-	-	-	-	-	-	-
	NC					-	-	-	-	2	-	2	-	2	2	2	2	2	-
	C	42.0	-	4 WAY 3 POS	80	1	-	-	-	-	-	-	-	-	-	-	-	-	-
	C	1.2	-	3 WAY 2 POS	7	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	C	3.5	-	3 WAY 2 POS	14	1	1	-	1	-	1	-	-	-	-	-	-	-	-
	NC					-	-	-	-	1	-	1	-	1	1	1	1	1	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	QUANTITY OF COMPONENT ON CONCEPT NUMBER													
						1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
SELECTOR VALVE-MAN	C	1.2	-	2 WAY 2 POS	7	1	-	-	1	-	-	-	-	-	-	-	-	-	-
	C	1.2	-	4 WAY 2 POS	14	-	-	2	-	-	-	-	-	-	-	-	-	-	-
	C	3.5	-	4 WAY 2 POS	30	-	2	3	1	3	1	3	-	3	3	3	3	3	3
	NC					-	-	-	-	-	-	-	-	-	-	2	-	-	-
	C	9.4	-	4 WAY 2 POS	55	2	3	-	2	-	2	-	-	-	-	-	-	-	-
	NC					-	-	-	-	3	-	3	-	3	3	2	3	3	-
	C	3.5	-	3 WAY 2 POS	14	3	-	-	1	-	1	-	-	-	-	-	-	-	-
TRANSFORMER HYDRAULIC	C	0.1	-	AREA RATIO = 1:1	2	-	-	-	-	-	-	-	4	-	-	-	-	-	-
	C	1.2	-	AREA RATIO = 1:1	2	-	-	-	-	-	-	-	3	-	-	-	-	-	-
	C	2.0	-	AREA RATIO = 1:1	3	-	-	-	-	-	-	-	1	-	-	-	-	-	-
	C	2.9	-	AREA RATIO = 1:1	3	-	-	-	-	-	-	-	3	-	-	-	-	-	-
	C	4.7		AREA RATIO = 1:1	11	-	-	-	-	-	-	-	3	-	-	-	-	-	-

*C = CRITICAL NC = NONCRITICAL

Table XLIII. Component List (Cont.)

NAME	*CLASS	FLOW (GPM)	RES/ACC FLUID VOL (CU. IN.)	MISC.	VOL (CU. IN.)	1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
						QUANTITY OF COMPONENT ON CONCEPT NUMBER													
TRANSFORMER HYDRAULIC	C	5.1	-	AREA RATIO = 1:1	11	-	-	-	-	-	-	-	6	-	-	-	-	-	-
↓	C	6.0	-	AREA RATIO = 1:1	11	-	-	-	-	-	-	-	18	-	-	-	-	-	-
↓	C	6.6	-	AREA RATIO = 1:1	11	-	-	-	-	-	-	-	3	-	-	-	-	-	-
↓	C	7.3	-	AREA RATIO = 1:1	11	-	-	-	-	-	-	-	30	3	3	-	-	-	-
↓	C	20.6	-	AREA RATIO = 1:1	15	-	-	-	-	-	-	-	4	18	18	-	-	-	-
↓	NC					-	-	-	-	-	-	-	-	6	-	-	-	-	-
↓	C	30.0	32.9	AREA RATIO = 1:1	101	-	-	-	-	-	-	-	9	9	9	-	-	-	-

Table XLIV Actuator and Component Totals

ITEM	CONCEPT NO.														
	1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
COMPONENT TOTALS:															
CRITICAL	67	0	91	91	71	54	72	49	133	91	89	42	42	59	67
NONCRITICAL	0	67	0	0	10	48	11	53	33	51	55	52	53	43	35
TOTAL	67	67	91	91	81	102	83	102	166	142	144	94	95	102	102
COMPONENT VOLUMES:															
CRITICAL	8.35	0	10.10	6.38	10.05	7.80	8.95	5.69	7.27	7.60	7.55	9.10	9.10	8.88	7.54
NONCRITICAL	0	0	0	0	2.66	4.24	.76	5.30	3.62	3.78	10.65	7.08	5.31	3.47	3.26
TOTAL	8.35	0	10.10	6.38	12.71	12.04	9.71	10.99	10.89	11.38	18.20	16.18	14.41	12.35	10.80
WIRING AND TUBING VOLUMES:															
CRITICAL	1.80	1.80	1.60	0.80	1.05	1.80	1.70	1.13	1.62	1.70	1.70	2.11	2.11	1.85	1.38
NONCRITICAL	0	0	0	0	65	1.00	1.20	.97	.58	.76	.95	1.64	.99	35	.52
TOTAL	1.80	1.80	1.60	0.80	1.70	2.80	2.90	2.10	2.20	2.46	2.65	3.75	3.10	2.20	1.90
TOTAL SYSTEM VOLUMES:															
CRITICAL	10.15	1.80	11.70	7.18	11.10	9.60	10.65	6.82	8.89	9.30	9.25	11.22	11.21	10.73	8.92
NONCRITICAL	0	8.35	0	0	3.31	5.24	1.96	6.27	4.20	4.54	11.60	8.72	6.30	3.82	3.78
TOTAL	10.15	10.15	11.70	7.18	14.41	14.84	12.61	13.09	13.09	13.84	20.85	19.94	17.51	14.55	12.70

Table XLV. Tube List

MATERIAL	DIAMETER (IN.)	WALL THICKNESS (IN.)	QUANTITY OF TUBING IN FEET ON CONCEPT NUMBER													
			1	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
STEEL	1/4	.016	119	302	-	85	330	142	355	276	310	310	292	310	288	313
		.040	-	-	413	-	-	-	-	-	-	-	-	-	-	-
	3/8	.022	261	139	-	67	224	185	153	336	188	188	196	188	224	77
		.061	-	-	124	-	-	-	-	-	-	-	-	-	-	-
	1/2	.028	66	99	-	42	195	82	192	52	256	256	116	200	195	78
		.081	-	-	122	-	-	-	-	-	-	-	-	-	-	-
	5/8	.035	9	19	-	34	124	69	73	61	33	33	66	33	39	55
		.101	-	-	51	-	-	-	-	-	-	-	-	-	-	-
	3/4	.042	73	108	-	98	80	20	-	53	51	51	-	33	80	107
	1	.058	22	51	-	-	[illegible]	-	47	182	245	245	-	-	51	51
	1 1/4	.065	33	-	-	36	-	49	7	44	-	-	-	-	-	-
ALUMINUM	1/4	.028	31	77	187	68	104	41	138	-	83	83	67	83	62	101
	3/8	.028	138	139	124	67	224	48	153	-	188	188	196	188	224	77
	1/2	.035	66	99	122	42	195	82	192	-	200	200	116	200	195	78
	5/8	.049	9	19	51	34	124	69	73	-	33	33	66	33	39	55
	3/4	.065	73	108	-	98	80	20	-	-	18	18	-	33	80	107
	1	.065	22	51	-	-	51	-	47	41	-	-	-	-	51	51
	1 1/4	.083	34	-	-	36	-	49	7	-	-	-	-	-	-	-
TOTAL LENGTH			956	1211	1194	707	1782	856	1437	1045	1605	1605	1115	1301	1528	1150

TABLE XLVI WIRE LIST

Wire Number	Diameter (in.)	Qty of Wire (Feet) on Concept		
		4	9	9A
2	0.89		410	178
4	0.78		73	118
6	0.63		92	
8	0.53		87	
12	0.32	28	252	
14	0.28	5	252	295
20	0.18	71		
22	0.16	113		
	Total Length =	217	1,166	601

APPENDIX II

VULNERABILITY/SURVIVABILITY DATA

1. PROBABILITY OF HIT ANALYSIS SAMPLE

The baseline system (Concept No. 1) was used to demonstrate the methods of calculating probability of hit for each subsystem. The aspect angle, $90^\circ/0^\circ$ (azimuth/elevation) was considered for this sample. In Table XLVII the components of subsystem 1 are shown with their total, shielded, and net projected areas; net projected areas for the remaining subsystems are shown. These net projected or vulnerable areas and their total are used in the following equation to determine the probability of hit, P_{HIT}, in each subsystem:

$$P_{HIT} = \frac{\text{Subsystem Vulnerable Area - Ft}^2}{\text{Total System Vulnerable Area - Ft}^2}$$

Then P_{HIT} for Subsystem 1 $= \frac{8.34}{27.18} = .307$

P_{HIT} for Subsystem 2 $= \frac{9.22}{27.18} = .339$

P_{HIT} for Subsystem 3 $= \frac{8.61}{27.18} = .317$

P_{HIT} for Subsystem 4 $= \frac{1.01}{27.18} = .037$

2. SURVIVABILITY SENSITIVITY ANALYSIS

A sensitivity analysis was conducted for the purpose of showing how a variation in number of hits on the aircraft would affect the probability of survival of a selected system. Three systems were arbitrarily selected: baseline (Concept No. 1), three-hydraulic sources (Concept No. 2), and electromechanical backup (Concept No. 4). The number of hits on the aircraft was assumed to range from 60 to 200, thus showing the effects of both increasing and decreasing the number of hits from the originally assumed value of 85. Eighty-five hits were used in analyzing each system in the study, because that number of hits would fulfill the kill criteria for the baseline system.

Figure 50 shows the results of the analysis. All systems are sensitive to the number of hits, with the three-hydraulic system showing more sensitivity when the number of hits exceeds 100. It is significant to note that, at each of the evaluation points, the relative survivability ranking of the three systems did not change. Thus the

TABLE XLVII

VULNERABLE AREA ANALYSIS - CONCEPT NO. 1

Sub-system	Item No.	Component	Proj. Area - Sq. In. (Aspect Angle $90^{\circ}/0^{\circ}$) Total	Shielded	Net
1	1	Pump	92.2	0	92.2
	2	Reservoir	129.0	0	129.0
	3	Accumulator	22.0	0	22.0
	4	Filter	44.2	8.8	35.4
	5	Filter	44.2	8.8	35.4
	6	Spoiler Actuator	35.1	0	35.1
	7	Spoiler Actuator	35.1	35.1	0
	8	Aileron Actuator	63.3	0	63.3
	9	Aileron Actuator	63.3	63.3	0
	10	UHT Actuator	73.4	0	73.4
	11	UHT Actuator	73.4	73.4	0
	12	Rudder Actuator	29.1	0	29.1
		Tubing			695.0
Subsystem No. 1 Total Net Projected (Vulnerable) Area = 1,210 $in.^2$ (8.34 ft^2)					
Subsystem No. 2 Total Net Projected (Vulnerable) Area = 9.22 ft^2					
Subsystem No. 3 Total Net Projected (Vulnerable) Area = 8.61 ft^2					
Subsystem No. 4 Total Net Projected (Vulnerable) Area = 1.01 ft^2					
Total System Vulnerable Area = 27.18 ft^2					

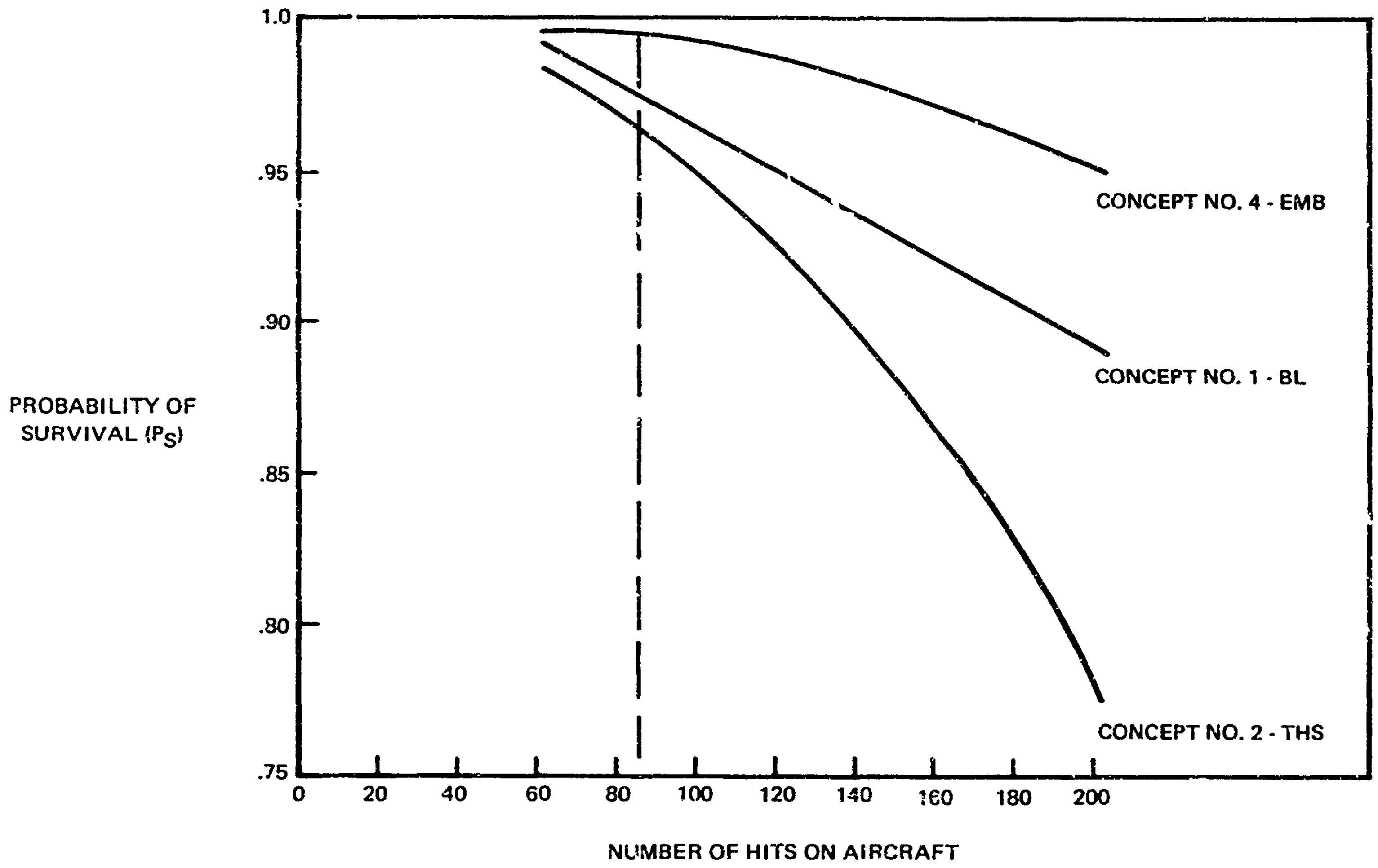


Figure 50. Probability of Survial (P_S) vs Number of Hits on Aircraft

electromechanical backup system has the higher survivability, regardless of the number of hits. Likewise, the three-hydraulic system had consistently the lowest survivability. Since the relative ranking of the systems throughout the range of hits examined was invariant, it is felt that the assumption of 85 hits is reasonable.

3. PROBABILITY OF SURVIVAL METHODOLOGY

A mathematical model was developed to determine the probabilities of survival of the various hydraulic systems. Each of the hydraulic systems evaluated was composed of a number of subsystems linked together in series or in parallel. Series linkage requires that all units must be functioning in order that the total system functions. In parallel linkage at least one of the parallel units must be functioning in order that the total system functions. Functioning of the system requires that a minimum number of subsystems be operative. Probability theory is used to determine the total system survival by combining the probabilities of hitting (and killing) the individual subsystems in the appropriate manner. Subsystem survival is dependent on area vulnerable to the projectile and on the probability of hit.

The computational model is concerned only with the projectiles which hit components within the subsystems and assumes that the hits are uniformly distributed over the aircraft. Required inputs are as follows: (1) total number of critical subsystems, (2) kill criteria (combination of subsystems which, if hit, would cause aircraft loss), (3) number of hits in system, and (4) single-shot probability of hit in each critical subsystem.

For illustrative purposes, derivation of a model applicable to the baseline system is presented. Derivation is based on a special case, but the resulting methodology is generalized such that the number of hits and number of subsystems can be varied.

Given:

(1) Four rounds versus four subsystems.

(2) P_i is probability of hitting iTH subsystem. Conversely, ($\overline{P}_i$) is the probability of not hitting the iTH subsystem and may be expressed as $(1 - P_i)$.

(3) One round may hit only one subsystem; any of the rounds may hit any of the subsystems.

(4) Probability of kill, given a hit, = 1.0.

(5) Aircraft kill requires kill of subsystems (S_1 and S_2) and/or (S_3 and S_4).

A partial list of possible combinations of four rounds hitting four subsystems are shown in tabular form; the possibility of aircraft kill is noted for each combination.

	Subsystem No.				Kill (k) or Surv. (s)	Case No.
	S_1	S_2	S_3	S_4		
	4	0	0	0	s	
	0	4	0	0	s	
	0	0	4	0	s	
	0	0	0	4	s	
Number	3	1	0	0	k	a
of	3	0	1	0	s	
Hits	3	0	0	1	s	
	1	3	0	0	k	b
	0	3	1	0	s	
	0	3	0	1	s	
	1	0	3	0	s	
	0	1	3	0	s	
	0	0	3	1	k	c
	1	0	0	3	s	
	0	1	0	3	s	
	0	0	1	3	k	d
	.	.	.	.	.	
	.	.	.	.	.	
	1	1	1	1	k	

The probability of killing the aircraft in the case (a) is developed through use of the binomial theorem.

Subsystem Number	No. Hits (R)	No. Req'd for Kill (X)
S_1	3	1
S_2	1	1

Aircraft kill results if at least one of three rounds hits Subsystem No. 1 and at least one of one round hits Subsystem No. 2, or

$$K_a = P(X_1 \geq 1)\ P(\ \_ \geq 1)$$

$$K_a = \left| \sum_{i=1}^{3} \binom{3}{i} P_1^{\,i}\ \bar{P}^{\,3-i} \right| \left| \sum_{j=1}^{1} \binom{1}{j} P_2^{\,j}\ \bar{P}_2^{\,1-j} \right|$$

$$K_a = \left| 3P_1^{\,1}\ \bar{P}_1^{\,2} + 3P_1^{\,2}\ \bar{P}_1^{\,1} + P_1^{\,3}\ \bar{P}_1^{\,0} \right| \left| P_2^{\,1}\ \bar{P}_2^{\,0} \right|$$

Similarly for case (b)

Subsystem Number	No. Hits (R)	No. Req'd. for Kill (X)
S_1	1	1
S_2	3	1

$$K_b = \left| 3P_2^{\,1}\ \bar{P}_2^{\,2} + 3P_2^{\,2}\ \bar{P}_2^{\,1} + P_2^{\,3}\ \bar{P}_2^{\,0} \right| \left| P_1^{\,1}\ \bar{P}_1^{\,0} \right|$$

All cases resulting in an aircraft kill must be analyzed in the same manner. When the expansion for each case has been completed, the probability of kill, P_K, for each group of subsystems can be developed.

Assuming that each of the round assignment combinations are equally likely to occur, P_K becomes a weighted average K_a, K_b ....

Thus:

$$P_K \text{ (subsys 1 \& 2)} = \frac{1}{NC} \Big| K_a(3,1) + K_b(1,3) + K_c(2,2) + 2\ K_d(2,1) + 2\ K_e(1,2) + 3\ K_f(1,1) \Big|$$

where K(m,n) denotes the kill of (m) rounds hitting Subsystem No. 1 and (n) rounds hitting Subsystem No. 2. NC is the total number of combinations possible,

$$NC = \binom{R+N-1}{R} = \binom{4+4-1}{4} = 35$$

and the coefficients of K(m,n) are the number of ways that the combination appears. (R) is number of rounds, and (N) is the number of subsystems.

Then:

$$P_K\text{ (subsys 1 \& 2)} = \frac{1}{NC} \sum_{I_1=1}^{R-1} \sum_{I_2=1}^{P-I_1} \binom{I_X+S-1}{S-1} K\,(I_1,I_2)$$

$$= \frac{1}{\binom{R+N-1}{R}} \sum_{I_1=1}^{R-1} \sum_{I_2=1}^{R-I_1} \binom{I_X+S-1}{S-1} \left[\sum_{i=1}^{I_1} \binom{I_1}{i} P_1^{\,i} \; \bar{P}_1^{\,I_1-i} \right]$$

$$\left[\sum_{J=1}^{I_2} \binom{I_2}{j} P_2^{\,j} \; \bar{P}_2^{\,I_2-j} \right]$$

$$= \frac{1}{\binom{R+N-1}{N}} \sum_{I_1=1}^{R-1} \sum_{I_2=1}^{R-I_1} \binom{I_X+S-1}{S-1} \left[1-\bar{P}_1^{\,I_1}\right] \left[1-\bar{P}_1^{\,I_2}\right] \qquad (1)$$

where $I_X = R-I_1-I_2$ and (S) is the remaining number of components on which $(R-I_1-I_2)$ rounds are spent.

The P_K(subsys. 3 & 4) is determined by the same method, and results in the same basic equation with appropriate substitutions

$$P_K\text{(subsys 3 \& 4)} = \frac{1}{\binom{R+N-1}{R}} \sum_{I_3=1}^{R-1} \sum_{I_4=1}^{R-I_3} \binom{I_X+S-1}{S-1}$$

$$\left[1-\bar{P}_3^{\,I_3}\right] \left[1-\bar{P}_4^{\,I_4}\right] \qquad (3)$$

The probability of kill of all subsystems is

P_K(subsys. 1, 2, 3 & 4) =

$$\frac{1}{\binom{R+N-1}{R}} \sum_{I_1=1}^{R-3} \sum_{I_2=1}^{R-I_1-2} \sum_{I_3=1}^{R-I_1-I_2-1} \left|1-\overline{P}_1^{\ I_1}\right| \left| 1-\overline{P}_2^{\ I_2}\right| \left|1-\overline{P}_3^{\ I_3}\right| \left|1-\overline{P}^{\ I_4}\right| \quad (4)$$

where:

$I_4 = R-I_1-I_2-I_3$

Aircraft probability of survival is the probability that at least one of the following conditions does not occur: kill of subsystems 1 and 2; kill of subsystems 3 and 4; or, kill of subsystems 1, 2, 3, and 4.

Then:

$$P_S = 1 - \left|P_K \text{ (subsys 1 \& 2)} + P_K \text{ (subsys 3 \& 4)} + P_K \text{ (subsys 1, 2, 3, \& 4)}\right|$$

This equation is valid only for the kill criteria specified; hence, it is used only for determining the probability of survival for a single baseline concept.

The probability of survival for other systems can be determined by revising equations (1) through (3), such that the equation and kill criteria are compatible. A revision of equation (1) can be used to determine the probability of survival when three out of a total "t" subsystems must survive.

P_K (subsys 1, 2 , & 3) =

$$\frac{1}{\binom{R+N-1}{R}} \sum_{I_1=1}^{R-2} \sum_{I_2=1}^{R-I_1-1} \sum_{I_3=1}^{R-I_1-I_2} \binom{I_X+S-1}{S-1} \left|1-\overline{P}_1^{\ I_1}\right| \left|1-\overline{P}_2^{\ I_2}\right| \left|1-\overline{P}_3^{\ I_3}\right|$$

and P_S (subsys 1, 2, & 3) = $1-P_K$ (subsys 1, 2, & 3).

APPENDIX III

RELIABILITY DATA

1. INTRODUCTION

The data presented in this appendix represent breakdowns of reliability assessment data summarized in Section VII and data required to support the analytical methods of MIL-STD-217A and MIL-STD-765A. Component arrangement by system and description are shown in Appendix I.

2. COMPONENT DATA SUMMARY

All components are tabulated in Table XLVIII with respective data classified according to usage: normal, high pressure, and pulsating flow. Normal usage applies to all components and systems not used for the other two distinct classifications. The MTBF and reliability values were used to determine reliability of the system in the normal, intermediate, and emergency mode assessments.

3. SYSTEM DATA DETERMINATION

Functional block diagrams were prepared for each system and its subsystems. These were used to determine the mean-time-between-failure and reliability values for each system in the normal, intermediate, and emergency performance modes. Functional block diagrams for the electromechanical backup system (Concept No. 4) are shown by Figures 51 through 54 as examples of the diagrams developed for each system. Figure 54 represents the combination of components required to complete the mission.

4. SYSTEM DATA SUMMARY

A summary of the results of reliability evaluations is presented in Table XLIX.

TABLE XLVIII. Component Reliability Data Summary

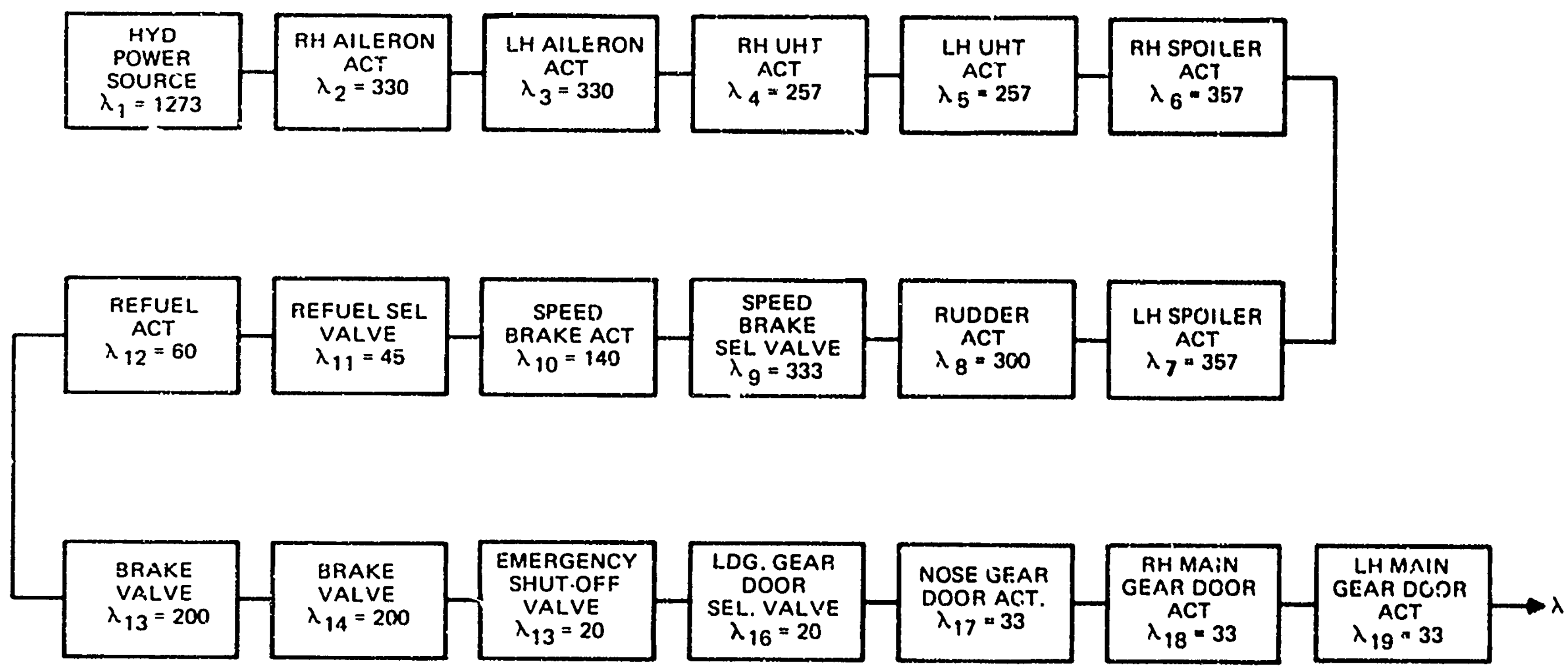
COMPONENT	NORMAL SYSTEM			HIGH PRESSURE SYSTEM			PULSATING FLOW SYSTEM		
	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)
ACCUMULATOR									
BRAKE	10000	.999850	9	6660	.999775	10			
EMERGENCY	10000	.999850	9						
POWER SUPPLY	25000	.999940	6	16700	.999910	10			
ACTUATOR									
AILERON	3000	.999505	11	2000	.999258	17	1900	.999220	23
ARRESTING GEAR	4500	.999670	12	3000	.999505	14	1923	.999220	20
FLAPS	9300	.999839	9	6200	.999759	13	2100	.999285	20
LANDING GEAR									
DOORS	30000	.999951	9	20200	.989796	13	2500	.999400	20
MAIN GEAR	6000	.999750	10	4000	.999624	14	1860	.999195	21
NOSE GEAR	6500	.999772	9	4400	.999658	14	1900	.999217	21
N.G. STEERING	910	.998351	25	605	.997525	32	714	.997902	35
REFUEL	16500	.999910	9	11100	.999865	14	2200	.999330	23
RUDDER	3300	.999550	10	2200	.999325	16	2040	.999265	23
SCREW JACK									
AILERON TAB	4000	.999625	11						
FLAPS	20000	.999925	8						
LDG. GEAR DOOR	20000	.999925	11						
UHT	4000	.999625	11						
SPEED BRAKE	7200	.999790	9	4750	.999685	14	1570	.999043	24
SPOILER	2800	.999465	12	1870	.999197	17	1600	.999067	24
UHT	3900	.999615	11	2600	.999422	16	2200	.999330	23
ALTERNATOR VALVE PACKAGE							1670	.999100	20
CONTROL PANEL, ELECTRICAL	2700	.999444	10						
CONSTANT SPEED DRIVE	1400	.998940	20						
ELECTRICAL POWER GENERATING PKG.									
SINGLE ENGINE DRIVE	710	.997890	48						
TWIN ENGINE DRIVE	600	.997516	58						
FILTER	1200	.999876	6	800	.999813	10			

Table XLVIII Component Reliability Data Summary (Cont.)

COMPONENT	NORMAL SYSTEM			HIGH PRESSURE SYSTEM			PULSATING FLOW SYSTEM		
	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)
GENERATOR, ELECTRICAL	5000	.999700	10						
MOTOR PUMP PACKAGE									
ELECTRICAL MOTOR	950	.998419	20						
ELECTRICAL MOTOR – CLUTCHING	1250	.998801	25						
FLYWHEEL	1260	.998807	30						
HYDRAULIC MOTOR	1200	.998763	33						
PUMP, HYDRAULIC	1000	.998500	25	670	.997750	32			
RESERVOIR	15000	.999899	7	10000	.999850	11			
SELECTOR VALVE PACKAGE	1330	.998420	44						
SHUT-OFF VALVE PACKAGE	1440	.998510	43						
TRANSFORMER									
AILERON							5100	.999708	12
ARRESTING GEAR							10000	.999850	11
BRAKE							10000	.999850	11
FLAPS							10000	.999850	11
LANDING GEAR									
DOORS							10000	.999850	11
MAIN GEAR							10000	.999850	11
NOSE GEAR							10000	.999850	11
N.G. STEERING							8000	.999813	11
REFUEL							10000	.999850	11
RUDDER							5700	.999738	12
SPEED BRAKE							5100	.999708	12
SPOILER							4800	.999685	12
POWER SUPPLY							4000	.999625	.2
UHT							6700	.999775	12

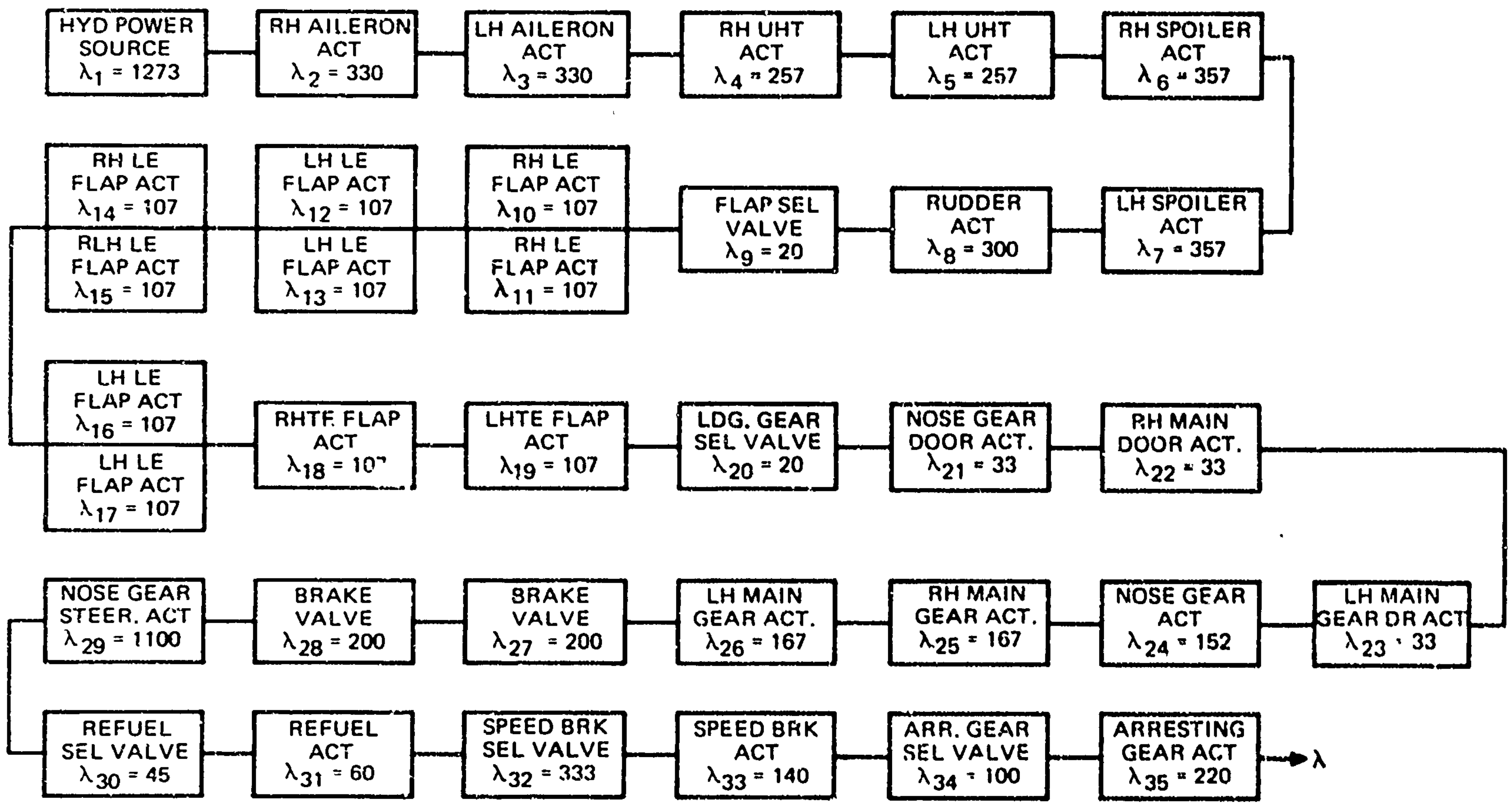
Table XLVIII Component Reliability Data Summary (Cont.)

COMPONENT	NORMAL SYSTEM			HIGH PRESSURE SYSTEM			PULSATING FLOW SYSTEM		
	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)	MTBF	RELIABILITY (R)	ASSESSMENT VALUE (AV)
VALVE									
BRAKE	5000	.999700	7	3300	.999550	12	2940	.999490	14
SELECTOR									
ARRESTING GEAR	10000	.999850	7	6700	.999775	11			
FLAPS	50000	.999970	6	33000	.999955	8			
LDG. GEAR & DOORS	50000	.999970	6	33000	.999955	8			
REFUEL	22000	.999933	6	14800	.999899	8			
SPEED BRAKE	3000			2000	.999250	16			
SELECTOR-EMERGENCY									
BRAKES	10000	999850	7						
FLAPS	10000	.999850	7						
LDG. GEAR & DOORS	10000	.999850	7						
SHUT-OFF-EMERGENCY	50000	.999970	6						
VOLTAGE REGULATOR	7700	.999805	8						



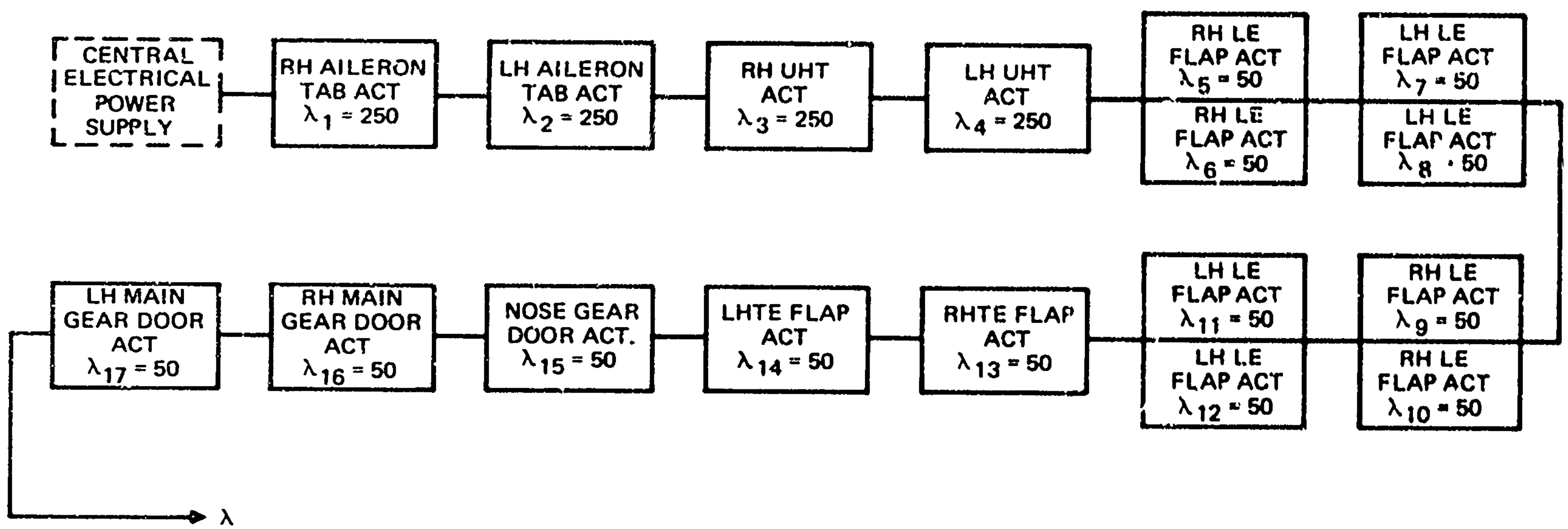
$$\lambda = \sum_{i=1}^{19} \lambda_i = 4578 \text{ FAILURES PER } 10^6 \text{ HOURS}$$

Figure 51. Concept No. 4 Electro Mechanical Back-Up Functional Block Diagram – Subsystem No. 1



$\lambda = \sum_{i-1}^{35} \lambda$ = 7554 FAILU:.:S PER 10^6 HOURS

Figure 52. Concept No. 4 Electromechanical Backup Functional Block Diagram Subsystem No. 2



$$\lambda = \sum_{i=1}^{17} \lambda_i = 1650 \text{ FAILURES PER } 10^6 \text{ HOURS}$$

Figure 53. Concept No. 4 Electromechanical Backup Functional Block Diagram – Subsystem No. 3

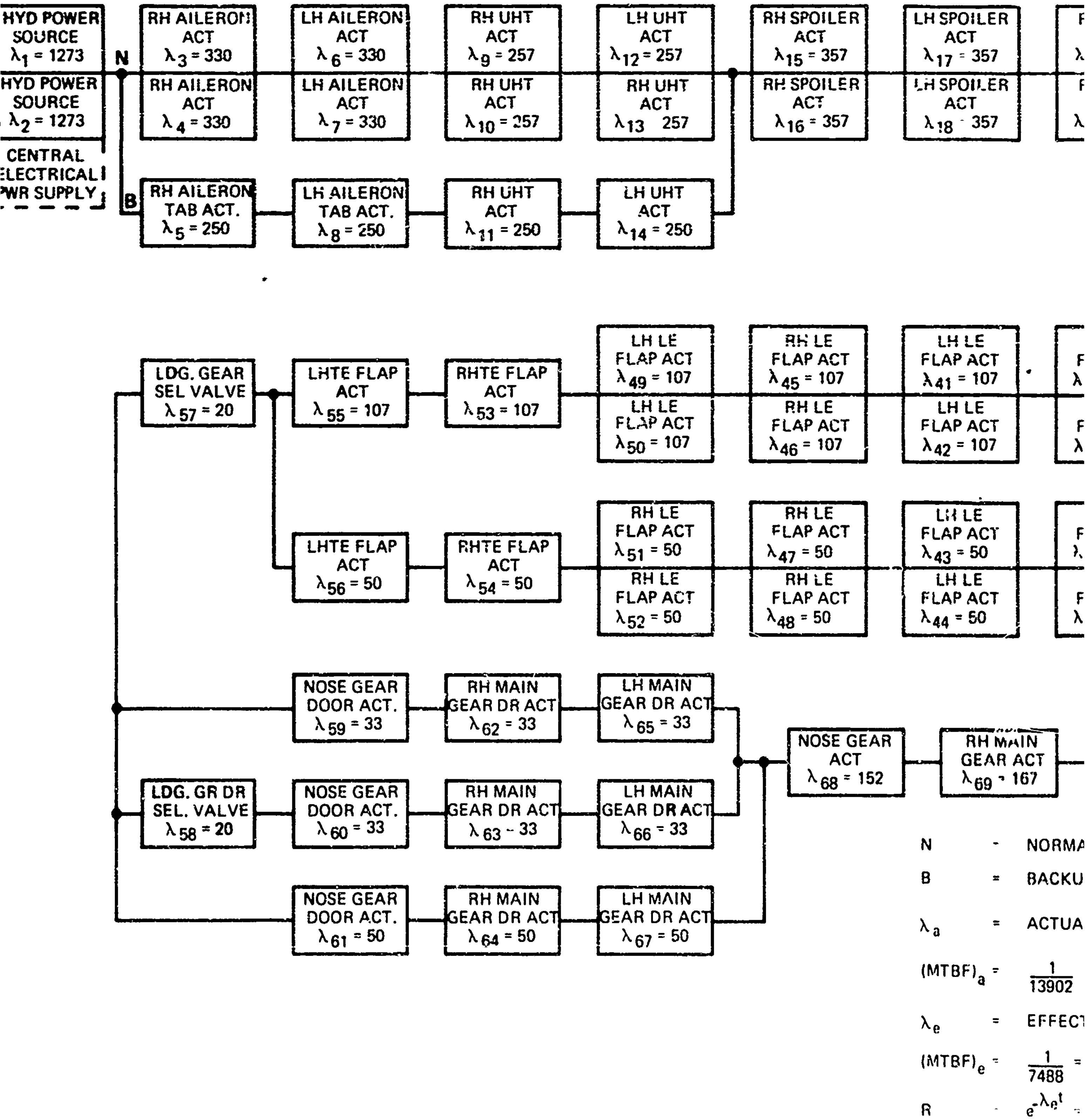


Figure 54. Co

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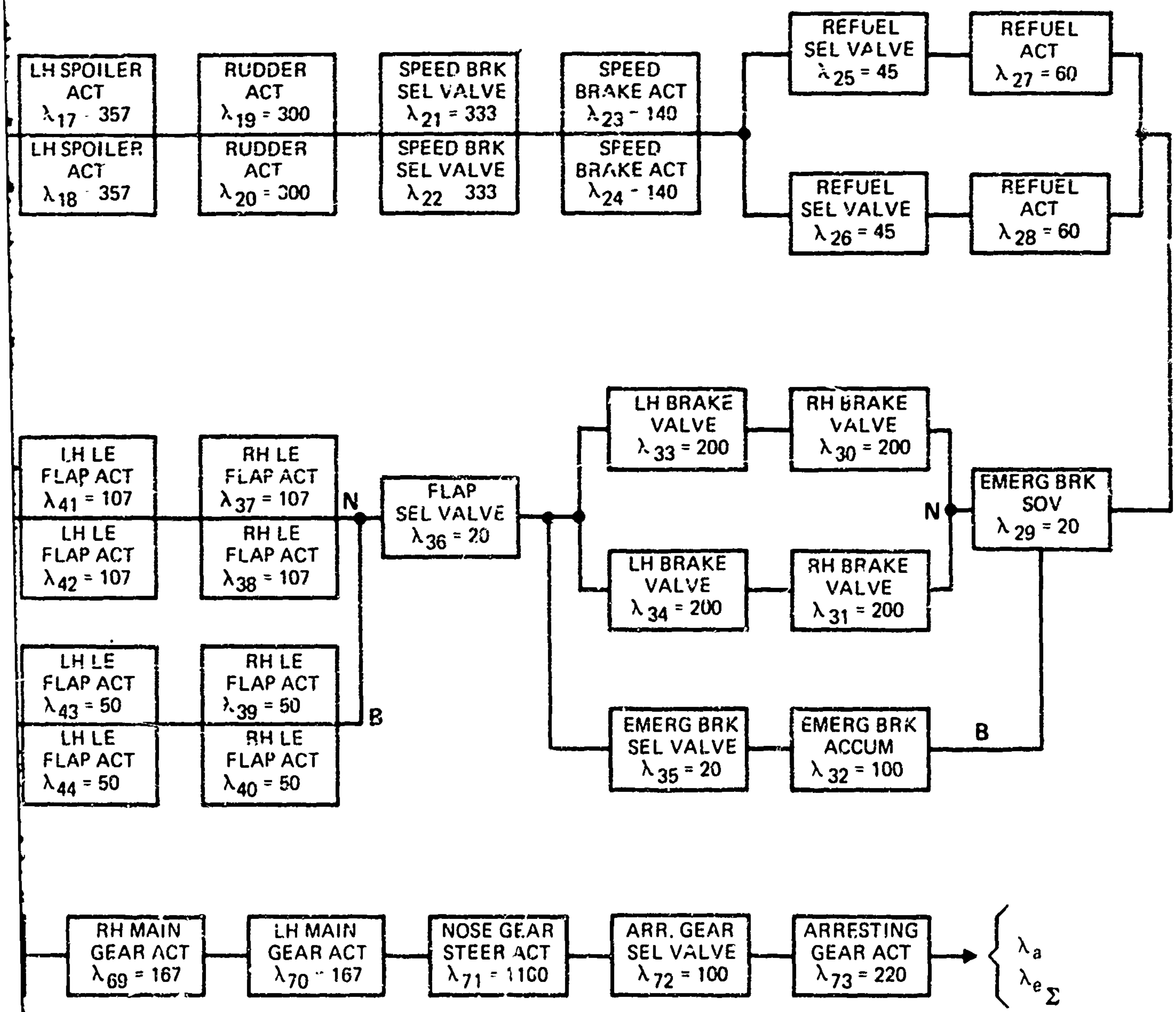
A.



N - NORMAL FUNCTIONAL FLOW PATH

B = BACKUP (STANDBY) FUNCTIONAL FLOW PATH

λ_a = ACTUAL FAILURE RATE = $\sum_{1}^{73} \lambda_i$ = 13902 FAILURES PER 10^6 HOURS

$(MTBF)_a = \frac{1}{13902} = 71.93$ HOURS

λ_e = EFFECTIVE FAILURE RATE = 7488 FAILURES PER 10^6 HOURS

$(MTBF)_e = \frac{1}{7488} = 133.55$ HOURS

R $e^{-\lambda_e t}$ $e^{-.007488 \times 1.5} = .988831$

Figure 54. Concept No. 4 Electromechanical Backup Functional Block Diagram - TOTAL SYSTEM

B.

TABLE XLIX. Reliability Evaluation Summary

CONCEPT NO.	CONCEPT	RELIABILITY ASSESSMENT ASSESS. VALUE (AV)	EMERG. MODE (R_{EM})	INTERM. MODE (R_{IM})	NORMAL MODE (R)	RANKING VALUE (RV)	MEAN-TIME-BET.-FAIL. (MTBF)	OPERATIONAL REL. (R_o)
1	BASELINE	653	.99995511	.99273	.979933	56.642	70.85	.966675
2	THREE HYDRAULIC SOURCES	876	.99999940	.999784	.979494	24.924	57.89	.961296
3	HIGH PRESSURE HYDRAULIC	1280	.99999791	.999505	.970237	37.284	38.14	.943198
4	ELECTRO-MECHANICAL BACK-UP PWR.	755	.99999987	.998199	.988831	19.713	71.93	.972657
5	FLYWHEEL POWER	1197	.99999958	.999830	.970496	34.838	39.07	.950310
6	ELECTRO-HYDRAULIC BACK-UP PWR.	846	.99999957	.994279	.984154	30.632	56.32	.967261
7	FIVE HYDRAULIC SOURCES	973	.99999984	.999909	.976556	27.681	50.15	.956441
8	PULSATING FLOW	2498	.99999967	.999799	.947742	65.564	19.76	.915972
8A	PULSATING FLOW	1491	.99999989	.999908	.965079	41.651	34.91	.937404
8B	PULSATING FLOW	1495	.99999990	.999916	.963638	42.784	33.73	.935616
9	ELECTRO-HYDRAULIC PWR. PKG.	1350	.99999975	.999932	.963101	41.780	28.74	.942874
9A	ELECTRO-HYDRAULIC PWR. PKG.	1204	.99999995	.999932	.967870	36.552	34.62	.947347
10	MOTOR PUMP ISOLATION	1212	.99999171	.999736	.970369	38.785	38.97	.950185
11	AUTOMATIC FAILURE ISOLATION	1610	.99999715	.999398	.963318	46.477	28.47	.943281

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APPENDIX IV

PERFORMANCE DATA

1. INTRODUCTION

The motorpump isolation system (Concept No. 10) is evaluated for performance penalties resulting from system efficiency, loss of one engine, loss of two hydraulic power sources, and function isolation. These four evaluations were weighted and combined into a performance rating value.

2. SYSTEM EFFICIENCY

The evaluation for system efficiency accounts for the efficiencies of the power sources and actuators. Actuator efficiency is intended to cover line efficiency or loss. Results of this evaluation are expressed as input power requirements or power drain on the engine. Input power is determined for the operating conditions which require the most power. This is the condition where the ailerons, unit horizontal tails, spoilers, rudder, and speed brake are required at different rates and loads. Design experience has shown that the sum of the required powers for this condition is approximately 60 percent of the sum of maximum powers. The portion of the motorpump isolation systems, which include only these functions, is shown in Figure 55. Maximum output power requirements are shown below each function; this power demand is shared equally by the number of subsystems shown at the function. Efficiencies used for the components are:

E_P	= Pump	90%
E_A	= Aileron Actuator	88%
E_U	= UHT Actuator	88%
E_S	= Spoiler	90%
E_R	= Rudder	90%
E_{SB}	= Speed Brake	86%
E_{MP}	= Hydraulic Motor-pump	80%

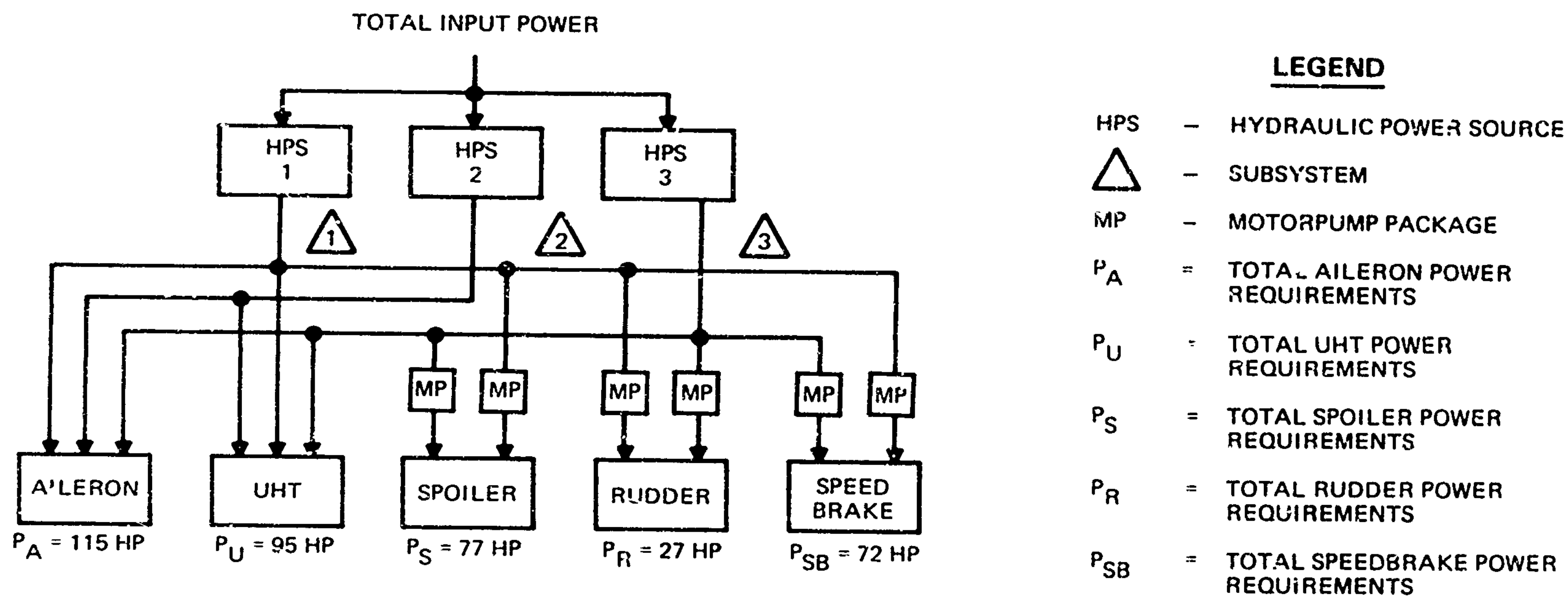

Figure 55. System Arrangement for Maximum Power Inputs – Concept No. 10.

a. Calculation of Input Power

(1) Subsystem 1

$$\text{Max Input Power} = \left\{ \frac{1}{3}\frac{P_A}{E_A} + \frac{1}{3}\frac{P_U}{E_U} + \frac{1}{E_{MP}} \left[\frac{1}{2}\frac{P_S}{E_S} + \frac{1}{2}\frac{P_R}{E_R} + \frac{1}{2}\frac{P_{SB}}{E_{SB}} \right] \right\} \frac{1}{E_P}$$

$$= \left\{ \frac{115}{(3)(.88)} + \frac{95}{(3)(.88)} + \frac{1}{.80} \left[\frac{77}{(2)(.90)} + \frac{27}{(2)(.90)} + \frac{72}{(2)(.86)} \right] \right\} \frac{1}{.90}$$

$$= 239 \text{ HP}$$

(2) Subsystem 2

$$\text{Max Input Power} = \left[\frac{1}{3}\frac{P_A}{E_A} + \frac{1}{3}\frac{P_U}{E_U} \right] \frac{1}{E_P}$$

$$= \left[\frac{115}{(3)(.88)} + \frac{95}{(3)(.88)} \right] \frac{1}{.90}$$

$$= 88 \text{ HP}$$

(3) Subsystem 3

Max Input Power = Input Power for Subsystem 1 = 239 HP

(4) Total System

Total Input Power = (230 + 88 + 239)(.60) = 340 HP

3. LOSS OF ONE ENGINE

The effect of losing each engine was examined. The effect was expressed in terms of power loss to each function. Weighting factors were applied to these losses, and the results were summed. The average penalty for both engines is then the penalty rating value. The analysis for this evaluation is shown in Table L.

4. LOSS OF TWO POWER SOURCES

The effect of losing any two power sources was examined. The effect was expressed in terms of power loss to each function. Weighting factors were applied to these losses, and the results were summed. The average penalty for each combination of power sources is then the penalty rating value. The analysis for this evaluation is shown in Table LI.

5. FUNCTION ISOLATION

All critical and noncritical functions are isolated by motor-pumps; thus the ratio of critical to noncritical in critical subsystems is zero.

6. PERFORMANCE RATING VALUE

The results of the above evaluations are normalized and combined with weighting factors applied to derive the performance rating value. This rating value is derived in Table LII.

TABLE L PENALTY RATING VALUE - ONE ENGINE LOST
(Concept No. 10)

Function	Weighting Factor	Engine 1		Engine 2	
		Function Loss	Rating	Function Loss	Rating
Aileron	4	1/3	4/3	1/3	4/3
UHT	4	1/3	4/3	1/3	4/3
L G Doors	4	0	0	0	0
Brakes	4	0	0	0	0
Rudder	3	1/2	3/2	1/2	3/2
Spoiler	3	1/2	3/2	1/2	3/2
Speed Brakes	3	1/2	3/2	1/2	3/2
Refuel	3	0	0	0	0
Flaps	2	0	0	0	0
Landing Gear	1	0	0	0	0
N G Steering	1	0	0	0	0
Arresting Gear	1	0	0	0	0
Total Rating	33	--	7.2	--	7.2

Penalty Rating Value = $\frac{7.2 + 7.2}{2} = 7.2$

PRV in % of Max Penalty = $\frac{7.2}{33} \times 100 = 21.6$

TABLE LI PENALTY RATING VALUE - TWO POWER SOURCES LOST
(Concept No. 10)

Function	Weighting Factor	Subsystems Lost: 1 and 3 Function Loss	Rating	1 and 2 Function Loss	Rating	2 and 3 Function Loss	Rating
Aileron	4	2/3	8/3	2/3	8/3	2/3	8/3
UHT	4	2/3	8/3	2/3	8/3	2/3	8/3
L G Doors	4	0	0	0	0	0	0
Brakes	4	0	0	0	0	0	0
Rudder	3	1	3	1/2	3/2	1/2	3/2
Spoiler	3	1	3	1/2	3/2	1/2	3/2
Speed Brake	3	1	3	1/2	3/2	1/2	3/2
Refuel	3	1	3	0	0	0	0
Flaps	2	0	0	0	0	1	2
Landing Gear	1	0	0	1	1	1	1
N. G. Steering	1	0	0	1	1	1	1
Arresting Gear	1	0	0	1	1	1	1
Total Rating	33	--	17.3	--	12.8	--	14.8

Penalty Rating Value $= \dfrac{17.3 + 12.8 + 14.8}{3} = 15.0$

PRV in % of Max. Penalty $= \dfrac{15.0}{33} \times 100 = 45.5$

TABLE LII PERFORMANCE RATING VALUE
(Concept No. 10)

Evaluation Parameter	Weighting Factor	Penalty Rating Value (PRV)	Normalized (PRV)	Weighted Rating
System Efficiency	40	7.5	.75	30.0
Loss of One Engine	10	7.2	.72	7.2
Loss of Two Power Sources	30	15.0	.71	21.3
Function Isolation	20	0	0	0
Total Penalty Rating Value =				58.5
Performance Rating Value = 100 - 58.5 = 41.5				

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APPENDIX V

COST

1. INTRODUCTION

Cost data developed for this study and supporting information are presented in this appendix. Included are the cost model used to estimate total system costs, cost summaries for the baseline system and three-hydraulic system derived by the cost delta method, and a listing of hydraulic system components and their cost ranges used to develop hydraulic system initial investment costs. Total system is defined as the aircraft including the hydraulic system; all system concepts are referred to as hydraulic systems.

2. COST MODEL

This cost model is used to develop preliminary total system cost estimates for a hypothetical attack aircraft in order to study effects on total system costs of various hydraulic system concepts. The general format has been derived from a model developed by VAD for advanced planning purposes. Estimating relationships used in the model are based on past VAD and other company studies. These relationships are based on 1967 dollars.

The model is divided into four sections: (1) Total System Costs; (2) Mission Dependent Factors; (3) Aircraft Costs; (4) Hydraulic System Costs. The Total System Cost section contains the major cost elements and relationships for determining each element. The Mission Dependent Factors section contains relationships which depend on mission definition and are required for estimating total system, aircraft, and/or hydraulic system costs. The Aircraft and Hydraulic System Costs sections contain the cost elements and relationships for estimating each element. Table LII is a listing of the various cost elements and factors used to estimate total system cost. Table LIV is a summary of constants and equations used.

a. Total System Cost

Total system cost has been divided into the two major cost elements of (1) aircraft less hydraulic system and (2) hydraulic system. Both of these elements contain initial investment, spares, and operating cost elements. Aircraft armor cost, for this study, is an additional element contained in the hydraulic system cost.

(1) Total system cost

CTO = CAC + CHY

(2) Total aircraft less hydraulic system cost

CAC = CA + CSPA + COPAC

(3) Total hydraulic system cost

CHY = CUHY + CSPH + COPHY + CAP

b. Mission-Dependent Factors

For this study, the operational life of the aircraft is assumed to be ten years during the 1970 to 1980 time period.

(1) Year of First Operational Flight

Y = 1970

(2) Last Year of Operational Life

ASL = 1980

(3) Aircraft Utilization

U = 35 flight hours per month

(4) Hydraulic System Life

Life for all hydraulic system concepts has been assumed to be for the life of the aircraft.

HSL = 12(U)(ASL-Y) hours

(5) Economic Factor

Cost estimating relationships used in this model are based on 1967 dollars. Costs for this study are based on 1970 dollars. Adjustment to 1970 dollars is accomplished by applying an economic factor to applicable cost elements.

$$FI = 1.03^{(Y-1967)}$$

(6) Mission Force Size

NAB = 1,000 aircraft

(7) Total Flight Hours

Total flight hours are based on mission force size, aircraft utilization, and operational life of the aircraft.

TFH = 12(NAB)(U)(ASL - Y)

(8) **Number of Ordnance Missions**

Total number of ordnance missions is the number of missions flown by the mission force to drop bombload during the system life. This factor is based on total flight hours and flight hours per mission. One ordnance mission is defined as dropping 0.3 of design gross weight in ordnance.

ORDMSN = TFH/FHM

(9) Weight of Bombload Carried Per Aircraft

Bombload weight is based on design gross weight and weight empty. Weight empty contains two variables, hydraulic system and armor-plate weight, which are traded off along with bombload.

WBM = WD - WECON - WAP - WHYT

(10) Number of Aircraft Required to Complete One Ordnance Mission

Number of aircraft is derived from the bombload required to complete one ordnance mission and the weight of bombload carried per aircraft.

ACMSN = 0.3 (WD)/WBM

(11) Total Number of Missions Required

Number of missions during system life is obtained by adjusting number of ordnance missions by the number of aircraft required to complete one ordnance mission.

TMSN = (ACMSN)(ORDMSN)

(12) Total Number of Missions Per Mission Force Aircraft

This factor is obtained from the operational life of the aircraft and the flight hours per mission.

ACMLF = TFH/FHM

(13) Total Number of Initial Investment Aircraft Required

Number of aircraft required per hydraulic system concept is derived from total number of missions required per system, number of missions per mission force aircraft, the probability of survival, and operational reliability of the aircraft which is assumed equal to that of the hydraulic system.

TNA = TMSN/((PSH)(RHY)(ACMLF))

(14) Total Number of Initial Investment Hydraulic Systems Required

Number of initial hydraulic systems required consists of those systems installed in the initial investment aircraft and an

additional number of systems to keep these aircraft operational. This number is obtained by adding to the initial aircraft quantity the quantity obtained by applying hydraulic system operational reliability to the difference between the initial aircraft quantity and the mission force size.

$$TNHY = TNA + (TNA - NAB)/RHY$$

c. Aircraft Costs

Aircraft costs in the model are determined for the aircraft less the hydraulic system. Relationships contained in this section, therefore, exclude all consideration of the cost elements associated with the hydraulic system, except for those elements involving crew and support personnel.

(1) Total Initial Investment

Total initial investment costs are determined from the number of initial aircraft required and the recurring flyaway cost per unit equipped (UE) **aircraft.**

$$CA = (CUA)(TNA)$$

(a) Aircraft

Various equations may be used to estimate the recurring flyaway cost of unit equipped (UE) **aircraft.** The following equations are used in this model and have been derived from a previous VAD study.

First estimate of initial investment cost per aircraft:

$$\begin{aligned} C1 = {} & \left|\left(2.80(TNA)\right)^{-.25} + 18.26(TNA)^{-.82}\right| \left|15.6(M)^{.656}\right| \left|(H)(10)^{-3}\right|^{.493} \\ & \left|(NE)/\left(.001(WD)\right)\right|^{.215} \left|(WE) - (WEN)\right| \left|(WD)(10)^{-3}\right|^{.20} \\ & (N)^{.197} \left|(WO)/\left((WS) + (WO)\right)\right|^{.141} \left|\left((WEN)/(WE)\right)^{.133}\right| (FI) + CE \end{aligned}$$

Second estimate of initial investment cost per aircraft:

$$\begin{aligned} C2 = {} & 9.57\left|(WO) + (WE) + (WEL)\right|^{.36} (N)^{.621} (M)^{.26} (WD)^{.698} \\ & \left|2.80(TNA)^{-.25} + 18.26(TNA)^{-.82}\right| (FI) + CE + CX1 \end{aligned}$$

Initial investment cost per aircraft less hydraulic system:

$$CUA = \left((C1) + (C2)\right)/2 - TCHY$$

The value of CUA is the cumulative average flyaway cost per aircraft less the hydraulic system. This cost includes prorated

cost of sustaining engineering, tooling, and flight test programs but does not include R and D.

Related equations:

$$CE = \left((.31979)(10)^3(13200 + .75(HPD)\right)^{.81626}\left((NE)(TNA)\right)^{-.12912}(NE)$$

$$CX1 = \left((1.1(WS)(M)(WD)(N)\right)^{.5}(10)^{-7}$$

Costs derived from these equations are based on 1967 dollars. Use of the inflation factor, FI, provides adjustment to any year desired.

Estimate of aircraft engine costs (CE) has been derived from estimating relationships developed by the Rand Corporation. The relationship has been modified to include the effect on cost of engine horsepower drain resulting from operation of the hydraulic system. This element is used as a measure of the performance of the hydraulic system.

(b) Initial Aircraft Spares

Initial spares for airframe, engines, and avionics are estimated as 20 percent of the total aircraft less hydraulic system flyaway cost.

$$CSPA = .2(CUA)(TNA)$$

(2) Operating Costs

(a) Aircraft Maintenance- **Base Level Maintenance Materials**

Materials costs only are considered in this category; the cost of maintenance personnel is included under Pay and Allowances. The estimating relationship that has been used for this cost element is that the annual cost of base maintenance materials equals 4.38 percent of the total cost of initial aircraft spares.

In order to determine the **prorata** share of maintenance materials costs for unit support aircraft, it is necessary to determine or assume the type and number of unit support aircraft in the organization and the annual flight hours of these aircraft. For purposes of this model, it is assumed that the organization's unit support aircraft are the C-123, U-3, and T-29, and that each attack aircraft commander flies 24 hours per year (two hours per month) as aircraft commander in each type. AFM 172-3 lists the base level maintenance materials cost per flight hour as $27.00, $15.00, **and** $16.00 for the C-123, U-23, and T-29 respectively in 1966. Thus, the total annual base level maintenance materials cost for each attack aircraft commander is $1,434.00 (1966 figures adjusted to 1967 by the use of an inflation factor), and this cost multiplied by the crew ratio equals the total annual cost for unit support **aircraft** per UE aircraft.

$$CMS = .0438\ (CSPA) + 1434\ (RC)\ FI$$

$$= .0438\ (.2CUA) + 1434\ (RC)\ FI = \left(.00876\ CUA + 1434\ (RC)(FI)\right)$$

(b) Aircraft Maintenance - **Depot Level Maintenance Materials,** Labor, and Contract

All depot level maintenance costs, including personnel, are represented in this category. If the costs are not available from AFM 172-3, the flight hour costs are estimated as \$14,962 plus 40.8 times the level-off cost of the aircraft in millions of dollars (the level-off cost of the aircraft is taken from that point on the learning curve at which no significant reductions in cost occur -- for the purposes of this model, this is assumed to occur at the 1000th unit), plus 52.61 times the design Mach number of the aircraft. This relationship was developed from RAND analyses of bomber aircraft and may not, therefore, be directly applicable to attack aircraft. However, the relationship has been assumed to apply to this study.

The depot maintenance cost for unit support aircraft may be derived from AFM 172-3 in the same manner as base level maintenance materials cost. Total annual depot costs for the C-123, U-3, and T-29 aircraft, using the same assumptions as above, are \$1,632 times the UE aircraft crew ratio.

$$CMD = \left((U)(179.544 + 597.6CUAK\ 10^{-6} + 631.32M) + 1632\ RC\right)(FI)$$

(c) Annual Replacement and Maintenance of Base Installations and Facilities

The annual cost of base facilities R&M should ideally be computed as a factor of the construction costs of the base plus an allowance for each man accommodated by the base. Since it is virtually impossible to determine the true base construction costs (most bases have had numerous modifications and additions over the years and have been converted for different uses), an estimating factor has been derived which relates this cost to the number of personnel (military only). The factor used in this model is \$721 per year per man.

$$CMR = 12{,}336 + 1017\ NPC + 1038\ NPR$$

(d) Ground Support Equipment Annual Replacement and Maintenance Costs

AGE

The annual cost of AGE R&M has been estimated as 10 to 15 percent of the initial investment in AGE. The average of these values, 12.5 percent, is used in this model.

$$CMA = .125(.04125)(CUA)(FI) = .00515625\ (CUA)(FI)$$

Other Equipment

Replacement and maintenance costs of other equipment must be computed, even though this equipment has no initial investment

cost to the system being analyzed. This cost is estimated as $170 per year per man required for the system.

$$CMO = 3300 + 257\ NPR + 252\ NPC$$

(e) **Aircraft POL (Petroleum, Oil, Lubricant)**

The annual cost of POL is determined by multiplying the average cost of fuel per gallon (including a factor for oil) by the annual flight hours and by the average consumption per flight hour. POL cost per gallon of fuel is estimated for this model as .10257 (.09657 for fuel plus .006 for oil) per gallon for JP. The annual flight hours are generally assumed for each analysis, and the average fuel consumption per flight hour is a technical input. If, however, the average consumption is not known, it can be estimated by determining the average maximum sortie flight time (based on average speed and range) and the total weight of fuel as taken from aircraft weight statements. In using this approach, the analyst should assume that only 90 percent of the fuel is used for this average mission, as general design practice is to determine mission length with a ten percent fuel reserve allowance.

AFM 172-3 may also be used to obtain hourly POL costs. Unit support aircraft POL can, in fact, be more rapidly derived in this way. Using the same assumptions previously made, the annual unit support POL cost per UE aircraft will equal $1,714 times the crew factor.

$$CML = (U)\ (1.23084F) + 1{,}714\ RC$$

(f) Supplies and General Services

This category consists of supplies not included elsewhere (such as for aircraft or base maintenance) and for general services such as the operations cost of ground vehicles, medical services, etc. RAND's estimate of an annual cost for this element of $412 per military man is used in this model.

$$CMG = (7{,}049 + 593\ NPR + 581\ NPC)\ (FI)$$

(g) Personnel Costs - Annual Pay and Allowances

This category includes pay, benefits, food or ration allowances, and other personnel allowances. The following equations have **been derived from empirical data taken from USAF UMD's (Unit Manning Document) and are the ones used in this study.**

$$CMP = 39190 + 7{,}866(NPR) + 13{,}232(NPC)$$

This equation may be applied directly to the prime mission aircraft being analyzed. Command support and unit support aircraft are not involved in the calculation as their support is implied in the constants of the equation.

The number of aircrew personnel, NPC, is derived from the number of positions in the aircraft, CS, and the crew ratio, RC.

NPC = (CS)(RC)

Organizational Maintenance Squadron, Field Maintenance Squadron, and Aircraft and Engine Squadron enlisted personnel numbers are determined from the maintenance manhour per flight hour by use of the formulas:

NPR = ((MMH)(U)/(PH))

MMH = MMHA + MMHH

MMH = Aircraft maintenance manhours per flight hour

MMHA = Aircraft less hydraulic system maintenance manhours per flight hour

MMHH = Hydraulic system maintenance manhours per flight hour

U = Monthly utilization per aircraft in hours

PH = Productive manhours per man per month

PH = 160 P

PHP = Estimated percent of available maintenance manhours per month

(h) Personnel Costs - Replacement Training and Travel

A certain number of the organization's personnel must be replaced each year. The following formula is based on the number of crew personnel and allows for personnel discharged and transferred.

CMT = 8135 + 954(NPR) + 11618(NPC)

(i) Training Ordnance

Annual cost of training ordnance per aircraft is the cost of an average aircraft load of ordnance multiplied by the loads expended each year per aircraft crew and by the number of crews per aircraft. No general cost inputs have been obtained for average aircraft ordnance and, therefore, this element is not considered in this study.

CMOR = 0.0

(j) Freight

Annual freight costs per aircraft have been established as equal to 1.5 percent of the following cost elements:

Fifty percent of the cost of attrition aircraft

Base level maintenance materials

Depot maintenance costs - (50% only on the assumption that materials are equal to half of the cost)

Ground support equipment replacement and maintenance costs

Supplies and general services (75% only on the assumption that supplies are equal to 75% and contracted services are equal to 25% of the total)

Training Ordnance

For aircraft less hydraulic system:

CMF = .015 (.5 CMAT + CMS + .5 CMD + CMA + CMO + .75 CMG + CMOR)

(k) Aircraft Attrition

During the operational life of an aircraft system, a certain number of aircraft will be destroyed or damaged beyond repair due to accidents or enemy gunfire. These aircraft must be replaced. Since the number of aircraft lost varies with the operational life of the system, the replacement cost is considered as an annual operating cost. As attrition rates usually are given as a factor of 100,000 flight hours, the annual cost of attrition per operational aircraft in this model is derived by multiplying the unit flyaway cost of the aircraft by the annual flight hours divided by 100,000.

CMAT = .00012(AT)(CUA)(U) per UE **aircraft**

Number of aircraft lost by attrition is derived by multiplying the attrition rate in aircraft per 1,000 missions by the number of missions required for ten years. Number of aircraft lost is expressed by the formula:

ATMSN = (XAT)(TMSN)/1,000

Related formulas are:

TMSN = (ACMSN)(ORDMSN)

ACMSN = .3(WD)/(WBM)

WBM = (WD) - (WECON) - (WAP) - (WHYT)

ORDMSN = (TFH)/(FHM)

TFH = 12(NAB)(U)(ASL - 1970)

Attrition rates may be related to a baseline attrition rate. Since attrition rate per 1,000 missions, XAT, is equivalent to the probability of kill, PK, per engagement, multiplied by 1,000, then, in general

$PK = XAT/1000$

$PK = (1 - (PS)(RE))$

where PS is probability of survival per engagement

RE is emergency mode system reliability.

By definition of probability of survival,

$PS = e^{-n}$

$PK = 1 - PS$

Therefore, PK is assumed to be a function of e to some negative exponential power, n.

$PK = e^{-n}$

Let the numbers 1 and 2 denote the baseline and the given quantities respectively to be related. Then,

$PK1 = e^{-n1}$

$PK2 = e^{-n2}$

Let $n2 = x(n1)$

Then, $PK2 = e^{-xn1}$

$Ln(PK1) = -n1$

$Ln(PK2) = -xn1$

Therefore,

$$x = \frac{Ln(PK2)}{Ln(PK1)}$$

From $PK2 = e^{-xn1}$ and $PK1 = e^{-n1}$

Then $PK2 = (e^{-n1})^x$

Therefore, $PK2 = (PK1)^x$

$$= (PK1)^{Ln(PK2)/Ln(PK1)}$$

But $PK1 = \left(1-(PS1)(RE1)\right)$

$1-(PS1)(RE1) = PK1$

$(PS1)(RE1) = 1-(PK1)$

$PS1 = \left(1-(PK1)\right)/(RE1)$

For this study,

PK1 = 54.96246 aircraft per 100 missions

RE1 = .99995511

PS1 = .97884

PK2 = 2.0 aircraft per 1,000 missions

RE2 = RE1

Since, $x = Ln(PK2)/Ln(PK1)$

$= Ln\ 54.96246/Ln2$

$= 2.14212$

Then $PK2 = (PK1)^{2.14212} = XAT$

$XAT = 1{,}000\left(1-(PSH)(RE1)\right)$

Where PSH = PS1

Therefore, knowing the baseline values of PK1, PSH, and RE1, and given values of PS2, then the given values may be related to the known baseline values. The assumption is made that in this study the emergency mode reliability values remain the same for each system concept.

Attrition rate per 100,000 flight hours, AT, is determined from XAT and mission time.

$$AT = \frac{\text{100,000 flight hours}}{\text{Hours per mission}} \times \frac{\text{aircraft lost}}{\text{1,000 Missions}}$$

$$= (100)\ (XAT)\ /\ (FHM)$$

(1) Ten-Year Operation

Cost elements in this category are divided into operating costs associated with maintenance only and other operating costs.

COPAC = CMAC + COOP

(m) Ten-Year Maintenance

Operating costs in this category are base level maintenance materials, depot level maintenance materials, labor and contract, AGE replacement and maintenance, other equipment replacement and maintenance, and base installations replacement and maintenance.

$$CMAC = (CMS + CMD + CMA + CMO + CMR)(TNA)(YF)$$

This element is used to establish a labor cost relationship between maintenance costs and number of maintenance actions per 1,000 flight hours in terms of average dollars for maintenance action. This dollar factor is applied to the number of maintenance actions per 1,000 flight hours predicted for each hydraulic system. Derivation of this factor is contained in Section 5 of this appendix.

(n) Ten-Year Other Operation

Operating costs in this category include aircraft POL, supplies and general services, pay and allowances, replacement training and travel, attrition, training ordnance, and freight.

$$COOP = (CML + CMG + CMP + CMT + CMAT + CMOR + CMF)(TNA)(YF)$$

d. Hydraulic System Costs

In this model, these costs are developed separately from the aircraft so that total ten-year costs for the hydraulic system alone may be obtained for each concept. Costs include initial investment (recurring only), initial spares, operating, and aircraft armor. Armor is considered as a part of the hydraulic system cost from the standpoint of adding armor to increase survivability of the aircraft by protecting the hydraulic system.

(1) Total Initial Investment

Initial investment costs are derived from estimated hardware material, assembly, installation, material handling, and checkout costs. A factor of 2 is applied to hardware material cost to account for assembly, installation, material handling, and checkout. A reliability cost factor is applied to material hardware costs to account for differences in costs to achieve predicted system reliability as related to the baseline system reliability.

$$CUHY = (HUA)(TNHY)$$

(a) Initial Investment Per Aircraft

$$HUA = (TCUHY + 2TCUHY)(RFC) = 3(TCUHY)(RFC)$$

(b) Hardware Material Cost Per Unit

This element is estimated from the components described for each concept.

TCUHY = input

(c) Reliability Cost Factor

An empirical factor has been derived from published literature to reflect cost changes between baseline and concept reliability. This factor is based on system mean-time-between-failure.

$$RFC = .061/(1/MTBFC)^{.545}$$

(d) Initial Spares

Initial spares quantity is included in the initial quantity of hydraulic systems required. Spares cost is determined from the difference between this quantity and the initial quantity of aircraft and hardware material cost.

CSPH = (TNHY - TNA)(TCUHY)(RFC)

(e) Armorplate

Armorplate costs include material and fabrication and installation costs. These have been estimated on a cost-per-pound basis. Costs per pound are estimated as \$4.50 for armorplate and \$.30 for fabrication and installation. A factor of 1.15 is used to account for structure material required for installation of armorplate.

$$CAP = \big((WAP)/1.15\big)(CAPD + .3)(TNA)(FI)$$

(2) Operating Costs

(a) Ten-year Operation

Elements in this category are divided into operating costs associated with maintenance personnel and material costs.

COPHY = CMHY + COPH

(b) Maintenance Personnel

Cost for this element includes pay and allowances for personnel associated with hydraulic system maintenance. Cost is based on maintenance manhours per flight hour, total flight hours, number of maintenance actions, and dollars per maintenance action.

CMHY = 2.64 (MMHH)(TFH) + .001(NMA)(DA)(TFH)

Maintenance manhours and number of maintenance actions per 1,000 flight hours have been estimated for each hydraulic system concept.

(c) Dollars per Maintenance Action

A relationship is established from the baseline system between ten-year maintenance costs and number of maintenance actions per 1,000 flight hours for the aircraft less hydraulic system. This relationship establishes a dollars per maintenance action factor to apply to the number of maintenance actions for each hydraulic system. Personnel pay and allowances cost for aircraft less hydraulic system is assumed to be equal to a dollars per hour pay rate ($2.64) times maintenance manhours per flight hour times total flight hours plus number of maintenance actions times dollars per maintenance action. Ten-year maintenance cost for aircraft less hydraulic system consists of personnel pay and allowances plus materials for replacement and maintenance. From these relationships, a dollars per maintenance action factor may be established.

As number of maintenance actions for the aircraft less hydraulic system is unknown, this number is assumed to be related to number of maintenance actions for the hydraulic system by the ratio of aircraft to hydraulic system maintenance manhours per flight hour.

$$(ANMA)/(NMA) = (MMHA)/)MMHH)$$

$$ANMA = (NMA)(MMHA)/(MMHH)$$

For aircraft less hydraulic system ten-year maintenance cost

$$CMAC = 2.64(MMHA)(TFH) + .001(ANMA)(DA)(TFH)$$

$$DA = \left(CMAC - 2.64(MMHA)(TFH)\right)/\left((.001(ANMA)(TFH)\right)$$

(d) Material Replacement and Maintenance

Operating costs in this category for the hydraulic systems are base and depot level maintenance materials, AGE replacement and maintenance materials, attrition, and freight.

$$COPH = (CMSH + CMDH + CMAH + CMATH + CMFH)(TNHY)(YF)$$

(e) Base Level Maintenance Materials

$$CMSH = .00876(HUA)(FI)$$

(f) Depot Level Maintenance Materials

$$CMDH = 597.6(HUA)(FI)(U)$$

(g) AGE Replacement and Maintenance Materials

$$CMAH = .00515625(HUA)(FI)$$

(h) Attrition

$$CMATH = (.00012)(AT)(HUA)(U)(FI)$$

(i) Freight

$$CMFH = .015 \left(.5(CMATH) + CMSH + .5(CMDH) + CMAH \right)$$

TABLE LIII

DEFINITION OF COST SYMBOLS

ACMLF	Total number of missions per aircraft during system life
ACMSN	Number of aircraft required to deliver 0.3 times design gross weight pounds of bombload
ANMA	Number of maintenance actions for aircraft less hydraulic system per 1,000 flight hours
ASL	Last year of aircraft system life
AT	Attrition rate in aircraft per 100,000 flight hours
ATMSN	Number of aircraft lost by attrition
CA	Total initial investment cost for aircraft less hydraulic system
CAC	Total ten-year cost for aircraft less hydraulic system
CAP	Total initial investment cost of armorplate
CAPD	Cost per pound for armorplate
CE	Total engine cost per aircraft
CHY	Total ten-year cost of hydraulic systems
CMA	Annual cost of AGE replacement and maintenance for aircraft less hydraulic system
CMAC	Ten-year maintenance cost for aircraft less hydraulic system
CMAH	Annual cost of AGE replacement and maintenance for hydraulic system
CMAT	Annual aircraft combat attrition for aircraft less hydraulic system
CMATH	Annual hydraulic system combat attrition
CMD	Annual cost of depot level maintenance materials, labor, and contract for aircraft less hydraulic system
CMDH	Annual cost of depot level maintenance materials for hydraulic system

TABLE LIII

DEFINITION OF COST SYMBOLS

(Continued)

CMF	Annual cost of freight for aircraft less hydraulic system
CMFH	Annual cost of freight for hydraulic system
CMG	Annual cost of supplies and general services
CMHY	Ten-year maintenance cost for hydraulic system
CML	Annual cost of aircraft POL
CMO	Annual cost of other equipment
CMOR	Annual cost of training ordnance
CMP	Annual pay and allowances for aircraft less hydraulic system
CMR	Annual cost of base installations and facilities replacement and maintenance
CMS	Annual cost of base level maintenance materials for aircraft less hydraulic system
CMSH	Annual cost of base level maintenance materials for hydraulic system
CMT	Annual cost of replacement training and travel
COPAC	Ten-year operating cost for aircraft less hydraulic system
COPHY	Ten-year operating cost for hydraulic system
CS	Crew size
CSPA	Initial cost of aircraft spares for aircraft less hydraulic system
CSPH	Initial cost of spares for hydraulic system
CTO	Total ten-year cost for complete aircraft system
CUA	Initial investment cost per aircraft less hydraulic system
CUAK	Aircraft cost at 1000th unit
CUHY	Ten-year hydraulic system cost

TABLE LIII

DEFINITION OF COST SYMBOLS

(Continued)

C1	First estimate of initial investment cost per aircraft
C2	Second estimate of initial investment cost per aircraft
DA	Dollars per maintenance action
F	Fuel consumption in gallons per hour
FHM	Flight hours per mission (average)
FI	Economic factor
H	Combat ceiling
HPD	Engine horsepower drain from hydraulic system
HSL	Hydraulic system life in hours
HUA	Initial investment cost of hydraulic system per aircraft
M	Design Mach number
MMH	Maintenance manhours per flight hour per aircraft
MMHA	Maintenance manhours per flight hour per aircraft less hydraulic system
MMHH	Hydraulic system maintenance manhours per flight hour
MTBF	Effective mean-time-between-failure of hydraulic system
MTBFC	Hydraulic system actual mean-time-between-failure
N	Ultimate load factor
NAB	Baseline force size less combat attrition and spare aircraft
NE	Number of engines per aircraft
NMA	Number of maintenance actions for hydraulic system per 1,000 flight hours

TABLE LIII

DEFINITION OF COST SYMBOLS

(Continued)

NPC	Total crew members per aircraft
NPR	Number of enlisted maintenance airmen per aircraft
ORDMSN	Total number of ordnance missions during system life
PA	Percent slope learning curve for aircraft
PH	Productive manhours per man per month
PHP	Estimated percent of available maintenance manhours per month
PHY	Percent slope learning curve for hydraulic systems
PSH	Probability of survival of hydraulic system
RC	Crew ratio
RE1	Emergency mode system reliability
RFC	Reliability cost factor related to baseline system reliability
RHY	Operational reliability of aircraft
TCUHY	Hydraulic system hardware material cost per unit
TFH	Total aircraft flight hours during system life
TMSN	Total number of missions required
TNA	Total number of initial investment aircraft required
TNHY	Number of initial investment hydraulic system required
U	Monthly flight hours per aircraft
WAP	Weight of armorplate
WAYT	Weight of hydraulic system
WBM	Weight of bombload carried per aircraft
WD	Design gross weight of aircraft
WE	Weight empty

TABLE LIII

DEFINITION OF COST SYMBOLS

(Continued)

WECON	Weight empty less hydraulic system
WEL	Weight of electronics
WEN	Weight of engines per aircraft
WO	Other equipment weight
WOCON	Other equipment weight less hydraulic system
WS	Structural weight
XAT	Aircraft attrition rate per 1,000 missions
Y	Year of first operational aircraft flight
YF	Number of years aircraft is operational

TABLE LIV

SUMMARY OF COST EQUATIONS

1. CONSTANTS

Year of first operational aircraft flight	Y = 1970
Last year of aircraft system life	ASL = 1980
Mission force size less combat attrition and spare aircraft	NAB = 1,000
Monthly flight hours per aircraft	U = 35
Flight hours per mission (average)	FHM = 1.5
Design gross weight of aircraft	WD = 45,000
Weight empty less hydarulic system	WECON = 30,256
Design Mach number	M = 2
Combat ceiling	H = 40,000
Number of engines per aircraft	NE = 2
Weight of engines per aircraft	WEN = 3,970
Ultimate load factor	N = 8
Structural weight	WS = 10,271
Weight of electronics	WEL = 925
Percent slope learning curve for aircraft	PA = 85
Percent slope learning curve for hydraulic system	PHY = 100
Estimated percent of available maintenance manhours per month	PHP = .525
Maintenance manhours per flight hour per aircraft	MMHA = 16
Crew ratio	RC = 1.55
Crew size	CS = 1
Fuel consumption in gallons per hour	F = 500
Annual cost of training ordnance	CMOR = 0

TABLE LIV

SUMMARY OF COST EQUATIONS

(Continued)

Cost per pound for **armorplate in dollars** CAPD = 4.5

Other equipment weight less hydraulic system WOCON = 6652

2. VARIABLES

a. Initial Investment Costs

Economic factor

$$FI = 1.03^{(Y-1967)}$$

Total aircraft flight hours during system life

$$TFH = 12(NAB)(U)(ASL - Y)$$

Total number of ordnance missions during system life

$$ORDMSN = TFH/FHM$$

Weight of bombload carried per aircraft

$$WBM = WD - WECON - WAP - WHYT$$

Number of aircraft required to deliver 0.3 of design gross weight as bombload

$$ACMSN = 0.3\ (WD)/(WBM)$$

Total number of missions required

$$TMSN = (ACMSN)(ORDMSN)$$

Aircraft attrition rate per 1000 missions

$$XAT = 1000\left(1-(PSH)(REl)\right)^{2.14212}$$

Total number of missions per aircraft

$$ACMLF = HSL/FHM$$

Total number of initial investment aircraft required

$$TNA = TMSN/\left((PSH)(RHY)(ACMLF)\right)$$

TABLE LIV

SUMMARY OF COST EQUATIONS

(Continued)

Total number of initial investment hydraulic systems required

$$TNHY = TNA + \big((TNA) - (NAB)\big)/(RHY)$$

Weight Empty

$$WE = WECON + WHYT$$

Other equipment weight

$$WO = WOCON + WHYT$$

Total engine cost per aircraft

$$CE = \big((.31979)(13200 + .75(HPD)\big)^{.81626}\big((NE)(TNA)\big)^{-.12912}(10)^{3}(NE)$$

Reliability cost factor related to baseline system reliability

$$RCF = .061/(1/MTBFC)^{.545}$$

Total cost of hydraulic system per aircraft

$$HUA = 3\ (TCUHY)(RFC)$$

Ten-year hydraulic system hardware material cost

$$CUHY = (HUA)(TNA)$$

Initial investment cost per aircraft less hydraulic system

$$CUA = (C1 + C2)/2 - HUA$$

First estimate of initial investment cost per aircraft

$$C1 = \Big(\sum_{i=1}^{9} (AX)_i\Big)(FI) + CE$$

$$AX(1) = (2.80)(TNA)^{-.25} + (18.26)(TNA)^{-.82}$$

$$AX(2) = (15.6)(M)^{.656}$$

$$AX(3) = \big((H)(10)^{-3}\big)^{.493}$$

$$AX(4) = \Big|(NE)/\big((.001)(WD)\big)\Big|^{.215}$$

$$AX(5) = WE - WEN$$

TABLE LIV
SUMMARY OF COST EQUATIONS
(continued)

$$AX(6) - \left((WD)(10)^{-3}\right)^{.20}$$

$$AX(7) = (N)^{.197}$$

$$AX(8) = \left|(WO)/\left((WS) + (WO)\right)\right|^{.141}$$

$$AX(9) = \left((WEN)/(WE)\right)^{.133}$$

Second estimate of initial investment cost per aircraft

$$C2 = \left(\sum_{i=1}^{5} (BX)_i\right)(FI) + CE + CX1$$

$$BX(1) = 9.57\left((WO) \div (WE) + (WEL)\right)^{.36}$$

$$BX(2) = (N)^{.621}$$

$$BX(3) = (M)^{.26}$$

$$BX(4) = (WD)^{.698}$$

$$BX(5) = AX(1)$$

$$CX1 = \left((1.1)(WS)(M)(WD)(N)\right)^{.5} (10)^{-7}$$

b. Operating Costs

Productive manhours per man per month

$$PH = 160\ (PHP)$$

Number of enlisted airmen per aircraft

$$NPR = (MMH)(U)/(PH)$$

Maintenance manhours per flight hour per airc aft

$$MMH = MMHA + MMHH$$

Total crew members per aircraft

$$NPC = (RC)(CS)$$

Annual cost of base level maintenance materials for aircraft less hydraulic system

$$CMS = .00876\ (CUA) + 1434\ (RC)(FI)$$

TABLE LIV

SUMMARY OF COST EQUATIONS

(continued)

Annual cost of depot level maintenance materials, labor, and contract for aircraft less hydraulic system

$$CMD = \left|\left((U)(179.44 + 597.6\,(CUAK)(10)^{-6} + 631.2\,(M)\right) + 1632(RC)\right|(FI)$$

Annual cost of AGE replacement and maintenance for aircraft less hydraulic system

$$CMA = .00515625\,(CUA)(FI)$$

Annual cost of aircraft POL

$$CML = 1.23084(F)(U) + 1714\,(RC)$$

Annual cost of other equipment replacement and maintenance

$$CMO = 3300 + 257\,(NPR) + 252\,(NPC)$$

Annual cost of base installations and facilities replacement and maintenance

$$CMR = 12336 + 1017\,(NPC) + 1038\,(NPR)$$

Annual cost of supplies and general services

$$CMG = \left(7049 + 593\,(NPR) + 581\,(NPC)\right)(FI)$$

Annual pay and allowances for aircraft less hydraulic system

$$CMP = 39190 + 7866\,(NPR) + 13232\,(NPC)$$

Annual cost of replacement training and travel

$$CMT = 8135 + 954\,(NPR) + 11618\,(NPC)$$

Initial cost of spares for hydraulic system

$$CSPH = (TNHY - TNA)(HUA)$$

Annual cost of attrition for aircraft less hydraulic system

$$CMAT = .000012(AT)(CUA)(U)$$

Attrition rate in aircraft per 100,000 flight hours

$$AT = (100)(XAT)/FHM$$

Annual cost of training ordnances

$$CMOR = 0$$

TABLE LIV

SUMMARY OF COST EQUATIONS

(continued)

Annual cost of freight for aircraft less hydraulic system

$$CMF = .015(.5(CMAT) + CMS + .15(CMD) + CMA + CMO + .75(CMG) + CMOR)$$

Initial investment cost of hydraulic system per aircraft

$$HUA = 3(TCUHY)(RFC)$$

Annual cost of base level maintenance materials for hydraulic system

$$CMSH = .00876(HUA)(FI)$$

Annual cost of attrition for hydraulic system

$$CMATH = .00012(AT)(HUA)(U)(FI)$$

Annual cost of freight for hydraulic system

$$CMFH = .015\big(.5(CMATH) + CMSH + .5(CMDH) + CMAH\big)$$

Number of years aircraft is operational

$$YF = ASL - Y$$

Ten-year operating cost for aircraft less hydraulic system

$$COPAC = CMAC + COOP$$

Ten-year material replacement and maintenance cost for hydraulic system

$$COPH = \big((CMSH) + (CMDH) + (CMATH) + (CMFH)\big)(TNHY)(YF)$$

Ten-year operating cost for hydraulic system

$$COPHY = CMHY + COPH$$

Dollars per maintenance action

$$DA = \big(CMAC - 2.64(MMHA)(TFH)\big)/\big(.001(ANMA)(TFH)\big)$$

Number of maintenance actions for aircraft less hydraulic system per 1,000 flight hours

$$ANMA = (MMHA)/(MMHH)(NMA)$$

Ten-year maintenance cost for aircraft less hydraulic system

$$CMAC = (CMS + CMD + CMA + CMO + CMR)(TNA)(YF)$$

TABLE LIV

SUMMARY OF COST EQUATIONS

(continued)

Ten-year maintenance cost for hydraulic system

CMHY = 2.64(MMHH)(TFH) + .001(NMA)(DA)(TFH)

Total initial investment cost for aircraft less hydraulic system

CA = (CUA)(TNA)

Total ten-year cost of hydraulic system

CHY = CUHY + CSPH + COPHY + CAP

Total initial investment cost of armorplate

CAP = ((WAP)/1.15)((CAPD) + .3)(TNA)(FI)

Initial cost of aircraft spares for aircraft less hydraulic system

CSPA = .2(CUA)(TNA)

Ten-year other operating cost for aircraft less hydraulic system

COOP = (CML + CMG + CMP + CMT + CMAT + CMOR + CMF)(TNA)(YF)

Total ten-year cost for aircraft less hydraulic system

CAC = CA + CSPA + COPAC

Total ten-year cost for complete aircraft system

CTO = CAC + CHY

Annual cost of AGE replacement and maintenance for hydraulic system

CMAH = 0.00515625 (HUA)(FI)

Annual cost of depot level maintenance materials for hydraulic system

CMDH = 597.6 (HUA)(FI)(U)

Table LV. Total System Cost Variation from Concept No. 1

PARAMETER	S/Δ	CONCEPT (ΔCOST IN BILLIONS)														
		1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
PROBABILITY OF SURVIVAL		.99804	.99978	.99925	.99974	.99999	.99998	.99998	.99998	1.0	1.0	1.0	1.0	1.0	.99998	.99986
ΔPS		0	.00174	.00121	.00169	.00195	.00194	.00193	.00194	.00196	.00196	.00196	.00196	.00196	.00193	.00182
ΔCOST[1]	$\frac{-20480}{.000001}$	0	-.03564	-.02478	-.03461	-.03994	-.03973	-.03953	-.03973	-.04014	-.04014	-.04014	-.04014	-.04014	-.03953	-.03727
RELIABILITY		.96668	.96668	.96130	.94320	.97266	.95031	.96726	.95644	.91598	.93741	.93562	.94288	.94735	.95019	.94328
ΔR		0	0	-.00538	-.02348	.00598	-.01637	.00058	-.01024	-.05070	-.02927	-.03106	-.02380	-.01933	-.01649	-.02340
ΔCOST[1]	$\frac{-5,296,000}{.00705}$	0	0	.00404	.01764	-.00449	.01230	-.00044	.00769	.03809	.02199	02333	.01788	.01452	.01239	01758
WEIGHT		1244	2744	1486	1732	1712	1839	1337	1540	2107	2035	2065	2414	2303	1790	1502
ΔW		0	1500	242	488	468	595	93	296	863	791	821	1170	1059	546	258
ΔCOST[1]	$\frac{2,040,000}{1\ LB}$	0	3.06000	.49363	.99542	.95463	1.21368	.18970	.60378	1.76035	1.6135	1.67468	2.38680	2.16036	1.11373	.52632
MAINTAIN-ABILITY-MMH		16.480	16.480	16.655	16.861	16.463	16.869	16.593	16.761	17.937	17.036	17.102	17.308	17.089	16.871	16.874
ΔMMH		0	0	.175	.381	-.017	.389	.113	.281	1.457	2.556	.622	.828	.609	.391	.394
ΔCOST[1]	$\frac{273,590,000}{1\ MMH}$	0	0	.04788	.10424	-.00465	.10643	.03092	.07688	.39862	.69930	.17017	.22653	.16662	.10697	.10779
HYD. SYS. COST		55825	55825	76051	143998	125942	80237	72420	77184	67553	39345	55652	141745	62988	79952	68061
ΔHC		0	0	20226	88173	69725	24412	16595	21359	11728	-16480	-173	85940	7163	24127	12236
ΔCOST[1]	$\frac{-8200}{\$1}$	0	0	-.16585	-.72302	-.57175	-.20018	-.13608	-.17514	-.09617	.13514	.00142	.70471	.58737	-.19784	-.10034
PERFORM-ANCE		288	288	308	455	290	271	290	292	423	423	344	454	390	340	308
ΔHP		0	0	20	167	2	-17	2	4	135	135	56	166	102	52	20
ΔCOST[1]	$\frac{192,500}{1\ HP}$	0	0	.00385	.03215	.00039	-.00327	.00039	.00077	.02599	.02599	.01078	.03196	.01964	.01001	.00385
TOTAL Δ COST		0	3.02436	.35877	.39182	.33419	1.08923	.04496	.47425	2.08674	2.45578	1.84024	3.32774	2.90837	1.00573	.51793

NOTE: 1. ΔCOST = (S/Δ) (ΔPARAMETER)

Table LVI. Total System Cost Variation from Concept No. 2

PARAMETER	CONCEPT (ΔCOST IN BILLIONS)															
	$/Δ	1	1A	2	3	4	5	6	7	8	8A	8B	9	9A	10	11
PROBABILITY OF SURVIVAL		.99804	.99978	.99925	.99974	.99999	.99998	.99998	.99998	1.0	1.0	1.0	1.0	1.0	.99998	.99986
ΔPS		-.00121	.00053	0.0	.00048	.00074	.00073	.00072	.00073	.00075	.00075	.00075	.00075	.00075	.00073	.00061
ΔCOST[1]	-12288 / .000001	-.01487	-.00651	0.0	-.00590	-.00909	-.00897	-.00885	-.00897	-.00922	-.00922	-.00922	-.00922	-.00922	-.00897	-.00750
RELIABILITY		.96666	.96668	.96130	.94320	.97266	.95031	.96726	.95644	.91598	.93741	.93562	.94288	.94735	.95019	.94328
ΔR		.00538	.00538	0	.01810	.01136	-.01099	.00596	-.00486	-.04532	-.02389	-.02568	-.01842	-.01395	-.01111	-.01802
ΔCOST[1]	-3,158,000 / .00685	-.00248	-.00248	0.0	.00834	-.00524	.00507	-.00275	.00224	.02089	.01101	.01184	.00849	.00643	.00512	.00831
WEIGHT		1244	2744	1486	1732	1712	1839	1337	1540	2107	2035	2065	2414	2303	1790	1502
ΔW		-242	1258	0	246	226	353	-149	54	621	549	579	928	817	304	16
ΔCOST[1]	1,155,100 / 1 LB	-.27953	1.45311	0.0	.28415	.26105	.40775	-.17211	.06237	.71732	.63415	.66880	1.07193	.94372	.35115	.01848
MAINTAIN-ABILITY-MMH		16.480	16.480	16.655	16.861	16.463	16.869	16.593	16.761	17.937	17.036	17.102	17.308	17.089	16.871	16.874
ΔMMH		-.175	-.175	0.	.206	-.192	.214	-.062	.106	1.282	2.381	.447	.653	.434	.216	.219
ΔCOST[1]	58,675,000 / 1 MMH	-.01026	-.01026	0.0	.01208	-.01126	.01255	-.00363	.00621	.07516	.13959	.02620	.03828	.02544	.01266	.01284
HYD. SYS. COST		55825	55825	76051	143998	125942	80237	72420	77184	67553	39345	55652	141745	62988	79952	68061
ΔHC		-20226	-20226	0	67947	49499	4186	-3631	1133	-8498	-36706	-20399	65714	-13063	3901	-7990
ΔCOST[1]	-4100 / $1	.08293	.08293	0.0	-.27858	-.20295	-.01716	.01489	-.00464	.03484	.15049	.08364	-.26943	.05356	-.01599	.03276
PERFORM-ANCE		288	288	308	455	290	271	290	292	423	423	344	454	390	340	308
ΔHP		-20	-20	0	147	-18	-37	-18	-16	115	115	36	146	82	32	0
ΔCOST[1]	98,300 / 1 HP	-.00197	-.00197	0.0	.01445	-.00177	-.00364	-.00177	-.00157	.01130	.01130	.00354	.01435	.00806	.00315	0.0
TOTAL ΔCOST		-.19645	1.51481	0.0	.03454	.03074	.39559	-.17422	.05564	.085030	.93733	.78481	.85441	1.02800	.34712	.06489

NOTE: 1. ΔCOST - (S/Δ) (ΔPARAMETER)

TABLE LVII

HYDRAULIC SYSTEM COMPONENT COSTS

COMPONENT	COST RANGE
Accumulator	134 - 268
Accumulator, Emergency	68 - 268
Actuator, Arresting Gear	1,190 - 2,980
Actuator, Aileron	640 - 3,110
Actuator, Aileron, Mechanical	2,160
Actuator, Flap	340 - 975
Actuator, Flap, Mechanical	1,200 - 2,160
Actuator, Landing Gear Door, Mechanical	2,160
Actuator, Main Gear	832 - 2,080
Actuator, Main Gear Door	250 - 2,160
Actuator, Nose Gear	375 - 936
Actuator, Nose Gear Door	305 - 2,160
Actuator, Nose Gear, Steering	1,230 - 3,080
Actuator, Refuel	200 - 647
Actuator, Rudder	933 - 2,585
Actuator, Speed Brake	465 - 1,175
Actuator, Spoiler	525 - 1,312
Actuator, UHT	625 - 3,060
Actuator, UHT, Mechanical	2,160
Brake Valve	214 - 642
Filter	133 - 144
Generator Package, Dual Drive	12,549

TABLE LVII

HYDRAULIC SYSTEM COMPONENT COSTS

(continued)

COMPONENT	COST RANGE
Generator Package	16,900
Motorpump, Electric	500 - 1,400
Motorpump, Engine-Driven	900 - 2,443
Motorpump, Hydraulic	1,050 - 1,520
Motorpump, Pneumatic	1,180 - 1,525
Rectifier, 1-Phase	80
Rectifier, 2-Phase	153
Rectifier, 3-Phase	225
Reservoir	250 - 634
Selector Valve, Arresting Gear	250 - 634
Selector Valve, Emergency	95 - 441
Selector Valve, Flap	95
Selector Valve, LG and Door	147 - 441
Selector Valve, Package	147 - 441
Selector Valve, Speed Brake	729 - 1,129
Selector Valve, Refuel	144 - 432
Shutoff Valve, Emergency	54
Shutoff Valve, Package	729 - 929
Transformer, Aileron	110
Tubing	336 - 1,068
Valve Package, Alternator	660

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APPENDIX VI

VALUE RATING DATA

1. GENERAL

A value rating method has been developed at Vought Aeronautics Division over the past several years which may be used to establish relative rankings of various system designs. The method is based on the theory that any aircraft system, from the component level through the total system level, has a function to perform, a weight, and a set of significant, measurable, and distinctive characteristics which can be used to identify uniquely a set of concepts. Application of the theory is to multiply two numbers, each representing significant function and weight requirements respectively of a system and to divide the resulting product by a number representing significant characteristics of the system. The numerical value of the resulting quotient is defined as the value rating for the system.

The theory is expressed mathematically by the value equation:

$$V = K\ (RF)\ (RW)/RC$$

where

RF = Function factor (equal to sum of function elements)

RW = Weight factor (equal to sum of weight elements which are related to pounds)

RC = Characteristic factor (equal to sum of characteristic elements)

K = Constant such that maximum (best) value rating equals 100

The higher the value rating number, the better the system is from the standpoint of characteristics chosen to identify the system. Concept rankings may be established by use of the value rating numbers.

Function elements are derived from significant measurable function parameters. These parameters represent the set of functional requirements of a system design to be emphasized. A function element may be obtained for such areas as aerodynamics, avionics, propulsion, structures, design, reliability, weight, maintainability, survivability, cost, or any other area requiring consideration.

Weight elements, related to pounds, are derived from measurable weight parameters affecting system weights. These parameters represent the set of weight requirements of a system design to be emphasized. A

weight element may be obtained for any one or several of the areas previously enumerated for function elements.

Either one or both sums for function and/or weight elements may be set equal to unity, if function and/or weight requirements need not be emphasized in the determination of the value rating and subsequent ranking.

Characteristic elements may be obtained from measurable parameters representing significant characteristics of the system design. A characteristic element may be obtained for any of the areas previously mentioned for function elements.

Examination of the equation shows that the value rating number increases as either RF or RW or both increase and RC remains constant or decreases. Therefore, a system increases in value if any one or more of these conditions exists for variations to a specified system.

By definition, the RF, RW, and RC factors are sums of functions, weight, and characteristics elements respectively. Numerical values of the RF and RW factors are increased only when any one or more of the element values is increased. These values increase as the numerical value of the affected parameter approaches the most desirable value for the parameter. Numerical values of the RC factor are decreased when any one or more of its element values is decreased. These values decrease as the numerical value of the affected parameter approaches the most desirable value of the parameter. A description of the derivation of function, weight, and characteristic element values is contained in Paragraph 3.

2. DEFINITIONS

a. Property - a quality or trait belonging and especially peculiar to an inanimate object.

b. Attribute - a set of one or more measurable properties peculiar to that attribute.

c. Characteristic - a set of one or more attributes which distinguishes and serves to identify that characteristic.

d. Functional requirement - a set of one or more distinctive attributes needed to identify the operations expected of a system.

e. Parameter - an arbitrary constant, each of whose values characterizes a member of a property.

f. Element - a basic part of a compound whole (sum of parts).

3. MATHEMATICAL DERIVATIONS

a. Function, Weight, and Characteristic Elements

Function and weight elements used in the function and weight factors respectively of the value equation are derived in the same manner. Except for one variation, characteristic elements are derived similarly. The following discussion applies to either function, weight, or characteristic elements.

One or more significant measurable parameters is selected to represent an element. The minimum and maximum expected values for each parameter are determined so as to include, but to be beyond, all possible values for the set of systems being evaluated. The best value of the parameter which is desirable to attain is established. This may either be the minimum, the maximum, or some value in between these two extremes. Actual parameter values developed for specific systems always will be between the two extreme values. A parameter may have any numerical value, either positive, negative, or zero. Notation used to establish equations for computing an element value is shown in Figure 56.

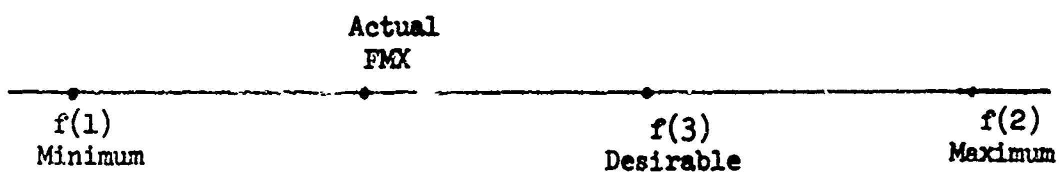

Figure 56

Element Notation

Each actual parameter value, FMX, is rated numerically for its nearness to the most desirable parameter value, f(3). This rating number varies from zero to one. It is relative to the range of values established from the maximum, f(2), and the minimum, f(1), for a specific parameter. As this rating number approaches zero, the nearer the parameter value is to the desirable value of the parameter. Thus, when an actual parameter value is equal to the desirable value, the rating value is zero which represents the best rating a parameter may have. In equation form, the rating number, PRN_i, for a parameter is:

$$PRN_i = \Big(FMX - f(3)\Big) / \Big(f(2) - f(1)\Big)$$

This rating number for a parameter is used in determining function, weight, and characteristic element values when the parameter is specified to be included in a particular element.

(1) Function Elements

Equation for function elements:

$$PFX_j = \sum_{i=1}^{nfj} (1-PRN_j)$$

where

PFX_j = jth function element

PRN_i = Absolute value of rating number for ith parameter in function element

nf_j = Number of parameters specified for jth function element

(2) Weight Elements

Equation for weight elements:

$$PWX_j = \sum_{i=1}^{nw_j} (1-PRN_i)$$

where

PWX_j = jth weight element

PRN_i = Absolute value of rating number for ith parameter in weight element

nw_j = Number of parameter specified for jth weight element

(3) Characteristic Elements

Equation for characteristic elements:

$$PCX_j = \sum_{i=1}^{nc_j} (HPRN_i)$$

where

PCX_j = jth characteristic element

PRN_i = Absolute value of rating number for ith characteristic element

nc_j = Number of parameters specified for jth characteristic element

The equations for function and weight elements are defined so that as parameter values approach the desirable values, the values of RF

and RW increase to a maximum value. This maximum indicates all desirable parameter values are attained for RF and RW.

The equation for characteristic elements is defined so that as parameter values approach desirable values, the value of RC decreases to a minimum. This minimum indicates all desirable parameter values are attained for RC.

Thus, when RF and RW are maximum and RC is minimum, the value rating number, V, will be 100, which is the best rating a system may have.

b. Function, Weight, and Characteristic Factor

(1) Equation for function factor:

$$RF = \sum_{j=1}^{mf} PFX_j$$

where

RF = Function factor

PFX_j = jth function element

mf = Number of function elements

(2) Equation for weight factor:

$$RW = \sum_{j=1}^{mw} PWX_j$$

where

RW = Weight factor

PWX_j = jth weight element

mw = Number of weight elements

(3) Equation for characteristic factor

$$RC = \sum_{j=1}^{mc} PCX_j$$

where

RC = Characteristic factor

PCX_j = jth characteristic element

mc = Number of characteristic elements

c. "K" Factor

Equation for K:

$$K = 100\,(NC)/\,(NF)(NW)$$

where

$$NC = \sum_{j=1}^{mc} nc_j$$

$$NF = \sum_{j=1}^{mf} nf_j$$

$$NW = \sum_{j=1}^{mw} nw_j$$

and

nc_j as defined in 3.a.(3)

mc as defined in 3.b.(3)

nf_j as defined in 3.a.(1)

mf as defined in 3.'.(1)

nw_j as defined in 3.a.(2)

mw as defined in 3.b.(2)

4. APPLICATION TO HYDRAULIC SYSTEM VULNERABILITY STUDY

The requirements of this study are (a) to evaluate each system on the basis of survivability, maintainability, performance, weight, reliability, hydraulic system cost, and total system cost; and (b) to use results of these evaluations to determine sytem rankings relative to all other systems, with emphasis on one or more of the evaluation areas.

In applying the value equation, the emphasized areas are included in the function factor, RF. Weight is used in the function factor so that equal emphasis will be assigned to each area. Thus, the weight factor, RW, is set equal to unity for this study. All areas are included in the characteristic factor, RC.

System evaluation results in a rating number from each area for each hydraulic system. These numbers are used as function and characteristic elements, as applicable, in the RF and RC factors, respectively, of the value equation. Rating numbers established by each area for each of the systems are summarized in Table LVIII. Included in this table are rating numbers for two hypothetical hydraulic systems. One system

represents a hydraulic system having characteristics better than any of the systems defined for this study, and the other represents a system having characteristics worse than any of the defined systems. These two hypothetical systems establish the range of values for each characteristic within which the characteristic values of the defined systems will fall. The value rating for the hypothetical best system is 100, and for the worst system it is 0. Value ratings for the defined systems are between these two values. The preceding equations were applied to Concept No. 6 as an example. Value rating elements are shown in Table LIX. The number of characteristic elements, NC, is six and the number of function elements, NF, is three. Since weight is included in the function factor, RF, the value for weight factor, RW, and number of weight factors, NW, is assumed as one. The multiplying factor, K, then becomes:

$$K = 100(NC)/(NF)(NW)$$

$$= 100(6)/(3)(1) = 200$$

Function factor, RF, is

$$RF = \Sigma PFX = 1.824$$

Characteristic factor, RC, is

$$RC = \Sigma PCX = 7.944$$

The value rating, V, then becomes

$$V = K(RF)(RW)/RC$$

$$= 200(1.824)(1)/7.944$$

$$= 45.92$$

5. DISCUSSION

Value ratings are based on a relationship of evaluation areas to be emphasized (function elements) to all the evaluation areas (characteristic elements). For the six evaluation areas, a total of 62 combinations are possible to choose from in selecting function elements. This number may be reduced by judicious selection of the areas to be emphasized.

Since this study is primarily concerned with survivability, this area is chosen as one of the function elements. Number of initial investment aircraft is an important consideration, since both initial investment costs and all operating costs are based on this quantity. Determination of the initial quantity of aircraft is based on probability of survival, operational reliability, and hydraulic system weight. Therefore,

reliability and weight areas are selected as function elements. The remaining areas, hydraulic system costs, performance, and maintainability all have lesser influences on total system cost and, therefore, are not considered as areas to be emphasized. The possible combinations of function elements are reduced to only one reasonable combination for this study.

Value ratings and ranking of systems using the function elements selected are contained in Table LX. In addition, ratings and rankings of systems for variations in choice of function elements are shown in the table.

TABLE LVIII

EVALUATION RATING SUMMARY

E V A L U A T I O N   A R E A

Concept No.	Hyd. Sys. Cost	Main-tainability	Perform-ance	Reli-ability	Surviv-ability	Weight
1	.512	4.034	78.300	56.642	1.00000	1244
1A	.230	4.034	78.300	56.642	.99826	2744
2	.377	5.720	74.000	24.924	.99879	1486
3	.448	5.883	87.900	37.284	.99831	1732
4	.261	5.033	75.200	19.713	.99805	1712
5	.201	7.080	44.100	34.838	.99806	1839
6	.174	5.686	64.100	30.632	.99806	1337
7	.189	6.127	47.900	27.681	.99804	1540
8	.200	13.174	75.400	65.564	.99804	2107
8A	.135	8.737	73.800	41.651	.99804	2035
8B	.163	8.693	63.100	42.784	.99804	2065
9	.334	8.349	69.300	41.780	.99804	2520
9A	.181	7.587	67.100	36.552	.99804	2390
10	.205	7.175	58.400	38.785	.99806	1790
11	.206	7.088	55.600	46.477	.99818	1468
12[1]	.100	3.000	30.000	10.000	.85051	900
13[2]	.700	20.000	100.000	100.000	1.05009	3000

Notes: 1. Hypothetical hydraulic system having best value rating of 100.

2. Hypothetical hydraulic system having worst value rating of 0.

TABLE LIX

VALUE RATING ELEMENTS
FOR CONCEPT NO. 6

Item	Hyd Sys. Cost	Maintain-ability	Perform-ance	Relia-bility	Surviv-ability	Weight
FMX	0.174	5.686	64.100	30.632	0.99806	1,337
f(1)	0.100	3.000	30.000	10.000	0.85051	900
f(2)	0.700	20.000	100.000	100.000	1.05009	3,000
f(3)	0.100	3.000	30.000	10.000	0.85051	900
PRN	0.123	0.158	0.487	0.229	0.739	0.208
PCX	1.123	1.158	1.487	1.229	1.739	1.208
PFX	-	-	-	0.771	0.261	0.792

TABLE LX VARIATION OF CONCEPT RANKING WITH VARIABLE FUNCTION ELEMENTS

Function and Characteristic Rating Symbols:

H - Hydraulic System Cost P - Performance S - Survivability
M - Maintainability R - Reliability W - Weight

VALUE RATINGS[a]

No. of Function Elements	3		3		3		3		4	
Function Elements	H, R, S		H, S, W		R, S, W		H, R, W		H, R, S, W	
Rank	Concept	Rating	Concept	Rating	Concept	Rating	Concept	Rating	Concept	Rating
1	7	48.95	6	48.57	6	45.90	6	61.40	6	50.98
2	6	48.04	7	46.18	7	44.95	7	60.05	7	50.03
3	4	45.59	11	44.23	2	42.96	4	54.12	4	45.32
4	5	45.01	5	40.76	4	42.73	11	52.39	11	44.05
5	8A	42.78	10	40.00	11	38.65	5	52.24	5	44.03
6	10	42.51	4	38.85	5	38.10	10	50.10	10	42.28
7	9A	42.19	8A	38.42	10	36.52	2	49.62	2	41.79
8	8B	41.80	8B	37.36	1	35.38	8A	47.37	8A	40.05
9	11	40.94	2	35.94	3	34.61	8B	46.11	8B	39.15
10	2	38.63	9A	32.64	8A	31.64	9A	42.88	9A	36.66
11	1A	33.46	8	32.52	8B	31.31	3	38.17	3	32.94
12	9	33.25	1	31.58	9A	28.95	1	36.79	1	31.84
13	8	31.61	3	28.47	9	24.89	8	35.12	8	30.53
14	3	30.53	1A	25.33	8	22.87	9	32.54	9	28.69
15	1	23.59	9	24.08	1A	18.72	1A	30.20	1A	26.93

Notes: A. Characteristic Factor Includes H, M, P, R, S, and W

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13 ABSTRACT

Aircraft hydraulic systems are presently designed with emphasis placed on satisfying performance requirements with minimum penalties in weight, reliability, maintenance, and costs. Results from limited war analyses have indicated the vulnerability of current hydraulic systems. Vulnerable areas of these systems were then protected with armorplate, resulting in mission penalties. A hypothetical airplane was defined, based on the F-8 configuration, with twin engines and a weight of 45,000 pounds. Conceptual system designs for this airplane were defined with increased redundancy incorporating backup or isolation features without the use of armorplate. These systems were assessed for vulnerability/survivability, reliability, maintainability, weight, performance, and system cost. These assessments provided system rating values and inputs for operational costs. The increase in redundancy (increase over the baseline system) resulted in most of the systems having probabilities of survival greater than the baseline system with armorplate. Further increase in probability of survival was achieved with the use of isolation and backup systems. A five-year development plan was prepared involving component development, system evaluation, and flight test evaluation.

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	ROLE	WT	ROLE	WT	ROLE	WT
Vulnerability Hydraulic System Electrohydraulic System Electromechanical System Pulsating Flow Hydraulics Hydraulic Failure Isolation						

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